Physical Scale Modelling of Smoke Contamination in Upper Balconies by a Balcony Spill Plume in an Atrium

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ABSTRACT

Whether the balcony spill plume will rise as a free plume or curl inwards towards the atrium structure is determinant upon a number of factors. Admittedly, not all the factors are well investigated and wholly understood, resulting in limited guidance for Fire Engineers on the behaviour of the balcony spill plume in an atrium. The only relevant guidance states that "*balconies which are shallow (< 2 m) will cause the rising spill plume to curl inwards towards the structure…… smoke-logging the balcony levels above the fire floor*". This guidance is based on limited number of smoke flow experiments in a model atrium.

This research project is primarily a qualitative examination of the behaviour of the balcony spill plume in an atrium. Its main objective is to systematically investigate the effects of varying balcony breadths, plume widths and fire sizes on smoke contamination in upper balconies through experimental work. A series of smoke flow experiments were conducted using a one-tenth physical scale model representing a six-storey atrium building. The scale model simulated a fire in an adjacent compartment connecting a fully open atrium. Visual observations and temperature measurements of the smoke flows were carried out.

From the experiment results, it was established that the extent of smoke contamination in upper balconies increased with decreasing balcony breadths, increasing plume widths and decreasing fire sizes. Further analysis of the experiment results showed that the aspect ratio of plume width to balcony breadth can be used to provide generic guidance to Fire Engineers in atrium design with respect to smoke contamination in upper balconies. In addition, an empirical correlation was developed to determine the height of smoke contamination and provide further guidance on smoke contamination in upper balconies.

All in all, this research project has met its objective and achieved its desired outcome. It provides more details and improved guidance for Fire Engineers on smoke contamination in upper balconies by a balcony spill plume in an atrium.

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NOMENCLATURE

SYMBOL	DESCRIPTION
b	Breadth of balcony (m)
c_{IMS}	Heat of combustion of Industrial Methylated Spirits (kJ/kg)
d	Depth of smoke layer beneath edge of Balcony 1 (m)
Fr	Froude number
H	Height of smoke contamination (m)
L	Characteristic length of scale model (m)
l	Characteristic distance of smoke layer beneath edge of Balcony 1 (m)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}_c$	Convective heat release rate (kW)
$\dot{Q}_T$	Total heat release rate (kW)
Re	Reynolds number
u	Averaged velocity of smoke layer beneath edge of Balcony 1 (m/s)
$\dot{V}_{IMS}$	Volume flow rate of Industrial Methylated Spirits (m^3/s)
w	Width of plume (m)

GREEK SYMBOL	DESCRIPTION
v	Kinematic viscosity of air (m^2/s)
ρ_{IMS}	Density of Industrial Methylated Spirits (kg/m^3)

1 INTRODUCTION

In today's modern architecture, an increasingly popular architectural feature in commercial and residential buildings is the atrium. Popular for its visual and spatial attractiveness, an atrium is typically a large space or void within a building, occupying several levels and connecting many adjacent spaces (e.g. shops, offices, balconies and corridors). The base of an atrium may have a functional use, ranging from reception areas to stalls and cafes, recreational activities or simply decorative purposes. An example of an atrium in a shopping mall is shown in Figure 1-1.

Figure 1-1: Atrium in Raffles City Shopping Centre [from Chen (2007)]

Unfortunately, the atrium can present significant fire risks to building occupants due to its lack of floor-to-floor separations. The lack of floor-to-floor separations allows fire and smoke to spread from the origin of fire to adjacent spaces in the building. Past experience with atrium fires have shown that there is less concern with the spread of fire within the building, particularly when the building is fully sprinklered (Sharry, 1973). Instead, of greater concern is the spread of smoke to areas or routes intended for the evacuation of building occupants. Therefore, it is important to have a good level of understanding on how smoke can spread in an atrium in the event of a fire.

1.1 Atrium Design

One of the several factors that can influence the spread of smoke in an atrium is the atrium design, particularly the interconnections between the atrium space and adjacent spaces. An increase in the number of interconnections is likely to increase the possibility of smoke spreading from the atrium space to the adjacent spaces. While it is recognised that the design of an atrium can be complex with a myriad of possible interconnections, four general types of atrium designs pertaining to Fire Engineering have been identified (Lougheed, 2000):

(i) 'Sterile Tube' atrium;
(ii) Closed atrium;
(iii) Partially open atrium; and
(iv) Fully open atrium.

1.1.1 'Sterile Tube' Atrium

For a 'sterile tube' atrium, the atrium space is separated from the adjacent spaces in the building by fire and smoke resisting barriers (e.g. fire resistant glazing). The base of the atrium has very restricted or non-functional use, and is generally used as a circulation area. Basically, the atrium serves as a sheltered area between separate parts of a building. A schematic diagram of the 'sterile tube' atrium is shown in Figure 1-2.

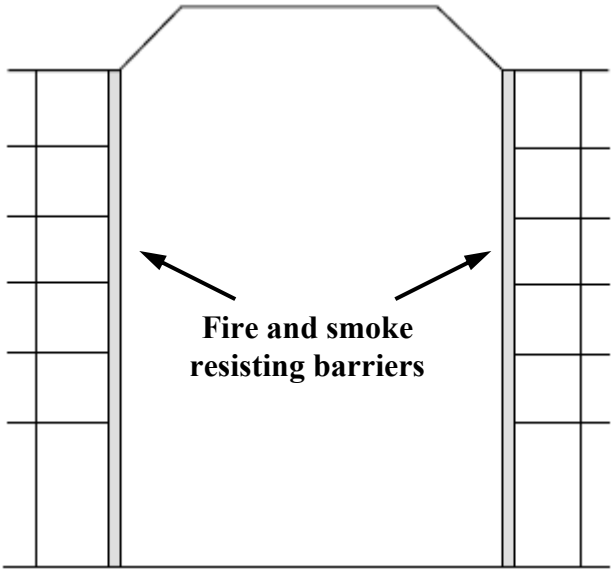

Figure 1-2: Schematic diagram of the 'sterile tube' atrium [adapted from Lougheed (2000)]

1.1.2 Closed Atrium

For a closed atrium, the atrium space is separated from the adjacent spaces in the building by non-fire resisting barriers (e.g. glass). These non-fire resisting barriers serve to prevent the spread of smoke, so long as they remain intact during a fire. The base of the atrium may have a functional use. A schematic diagram of the closed atrium is shown in Figure 1-3.

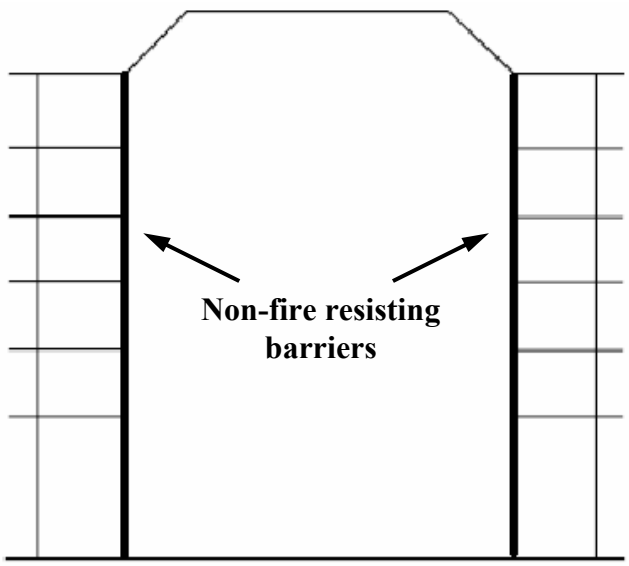

Figure 1-3: Schematic diagram of the closed atrium [adapted from Lougheed (2000)]

1.1.3 Partially Open Atrium

For a partially open atrium, some of the adjacent spaces on lower levels of the building are open to the atrium space. The adjacent spaces on the remaining upper levels are closed off by non-fire resisting barriers. The base of the atrium may have a functional use. A schematic diagram of the partially open atrium is shown in Figure 1-4.

1.1.4 Fully Open Atrium

For a fully open atrium, the adjacent spaces on all levels of the building are open to the atrium space. The base of the atrium may have a functional use. A schematic diagram of the fully open atrium is shown in Figure 1-5. In the schematic diagram, balconies are shown to extend from the openings of the adjacent spaces into the atrium space.

In maximising the use of space, the fully open atrium has the most number of interconnections between the atrium space and adjacent spaces. As a result, the possibility of

smoke spreading to the adjacent spaces is likely to be most significant. Hence, this research project will focus on the fully open atrium.

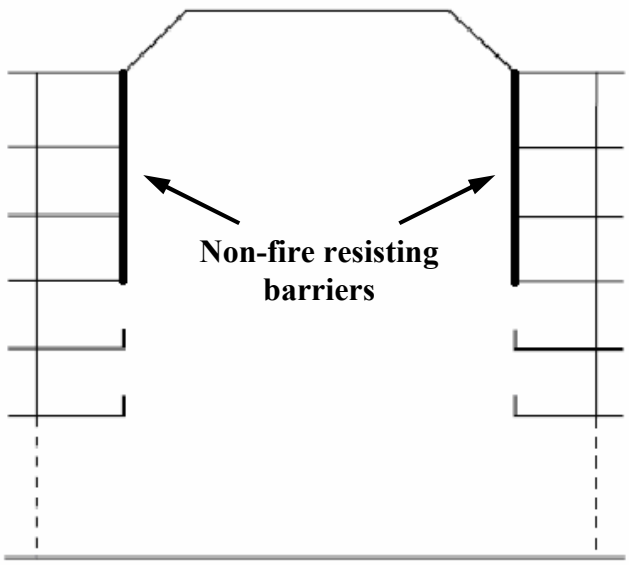

Figure 1-4: Schematic diagram of the partially open atrium [adapted from Lougheed (2000)]

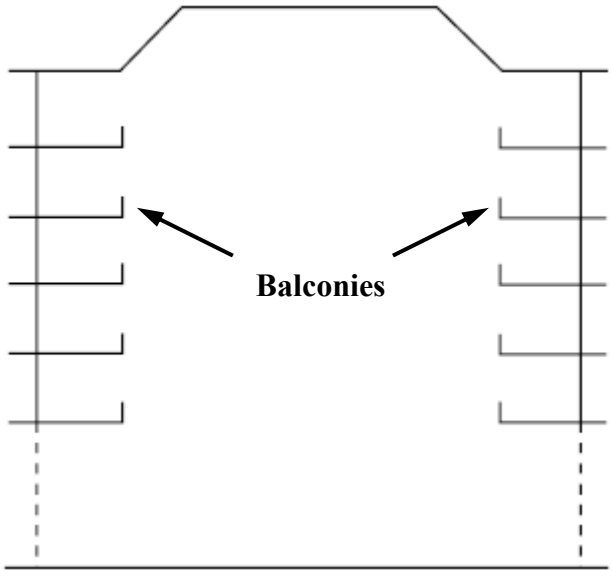

Figure 1-5: Schematic diagram of the fully open atrium [adapted from Lougheed (2000)]

1.1.5 Smoke Management

For some atrium designs, smoke management is pertinent to the safety of the building occupants in the event of a fire. One of the key smoke management approaches described by Morgan *et al* (1999) is a smoke and heat exhaust ventilation system (SHEVS). This system

provides smoke and heat exhaust from the upper levels of an atrium, in order to maintain a clear layer beneath a buoyant stratified smoke layer. As a result, tenable conditions are created to enable the safe evacuation of building occupants. The system may be mechanically driven by exhaust fans or naturally driven by the buoyancy of hot smoke. A schematic diagram of the concept of a SHEVS is shown in Figure 1-6. This research project utilises the concept of a SHEVS for smoke management in the physical scale model (described in detail in Section 3.2).

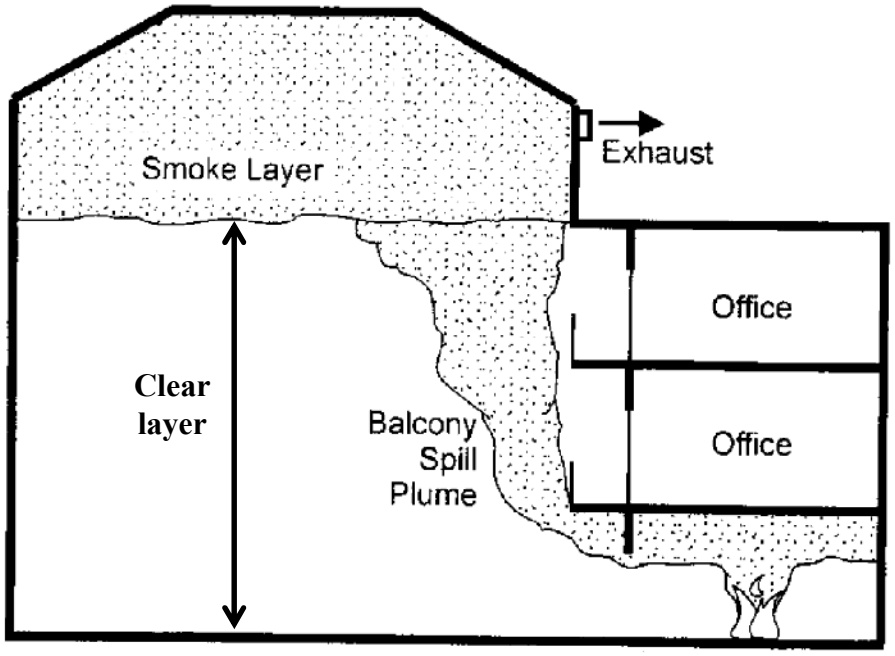

Figure 1-6: Schematic diagram of the concept of a SHEVS [adapted from Klote & Milke (2002)]

1.2 Balcony Spill Plume

Apart from the interconnections between the atrium space and adjacent spaces, the spread of smoke in an atrium may be dependant on the volume of smoke produced. The larger the volume of smoke produced, the greater the possibility of smoke spreading from the atrium space to the adjacent spaces. A large volume of smoke is produced when large amounts of air are entrained into a rising smoke plume. For different types of smoke plumes, the amount of air being entrained varies (Klote & Milke, 2002). Five types of smoke plumes are described by Klote and Milke (2002), namely axisymmetric plume, wall plume, corner plume, window plume and balcony spill plume. This research project is concerned with the balcony spill plume as the source of smoke.

1.2.1 Plume Development

When a fire occurs in an adjacent space that opens directly to an atrium, hot smoke from the fire will flow horizontally towards the opening. If the smoke is not contained within the adjacent space, it will flow out of the opening. If a balcony extends from the opening, the smoke will flow beneath the balcony towards the free edge of the balcony. The smoke will then 'rotate' about the balcony edge and rise vertically, entraining large amounts of air as it rises. This sequence of smoke flows shown in Figure 1-7 is commonly known as the balcony spill plume.

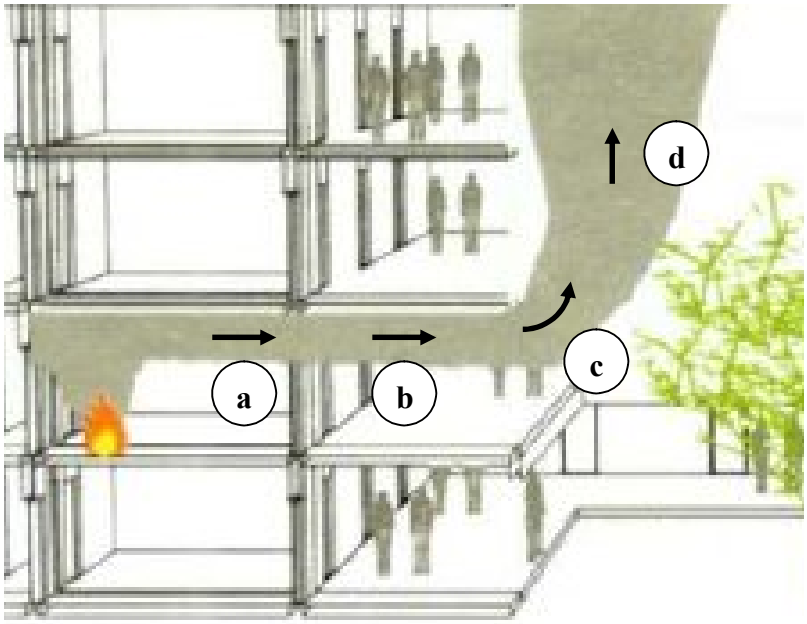

Figure 1-7: Balcony spill plume: a – Flow out of opening; b – Flow beneath balcony; c – 'Rotation' about balcony edge; d – Vertical rise [adapted from Morgan *et al* (1999)]

1.2.2 Plume Behaviour

In Figure 1-7, the balcony spill plume is described and depicted in an idealised manner, where the spill plume rises vertically without contaminating the upper balconies. The balcony spill plume is said to rise vertically as a free plume, where the entrainment of air occurs on both sides of the spill plume as shown by the arrows in Figure 1-8.

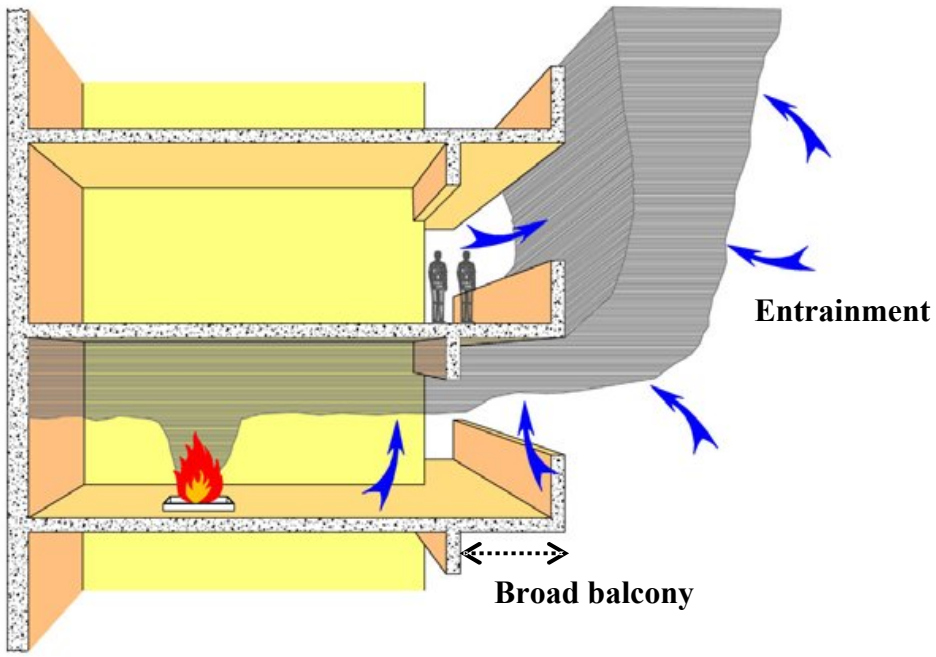

Figure 1-8: Balcony spill plume rises as free plume [adapted from Morgan *et al* (1999)]

Whether the balcony spill plume will rise vertically as a free plume is determinant upon a number of factors. For example with reference to Figure 1-8, the balcony has to be sufficiently broad to allow air to flow between the rising spill plume and the atrium structure, thereby enabling the entrainment of air on both sides of the spill plume. Another factor will be the momentum of the balcony spill plume when 'rotating' about the balcony edge. If the momentum is sufficiently high, the spill plume will project beyond the balcony edge to allow air to flow between the rising spill plume and the atrium structure.

On the other hand, the balcony spill plume may curl inwards towards the atrium structure, as shown by the arrows in Figure 1-9. Whether the spill plume curls inwards is determinant upon similar factors. For example, the balcony is likely to be so narrow that air cannot flow between the rising spill plume and the atrium structure. Entrainment of existing air by the rising spill plume on the side nearest to the atrium structure causes static pressure to fall in the region between the spill plume and atrium structure. This low-pressure region will cause the spill plume to curl inwards towards the atrium structure and contaminate the upper balconies. This is known as the Coanda effect (Cox, 1995). Alternatively, the momentum of the balcony spill plume when 'rotating' about the balcony edge is likely to be so low that the spill plume does not project out sufficiently to allow air to flow between the rising spill plume and the

atrium structure. As a result, the spill plume will also curl inwards towards the atrium structure and contaminate the upper balconies.

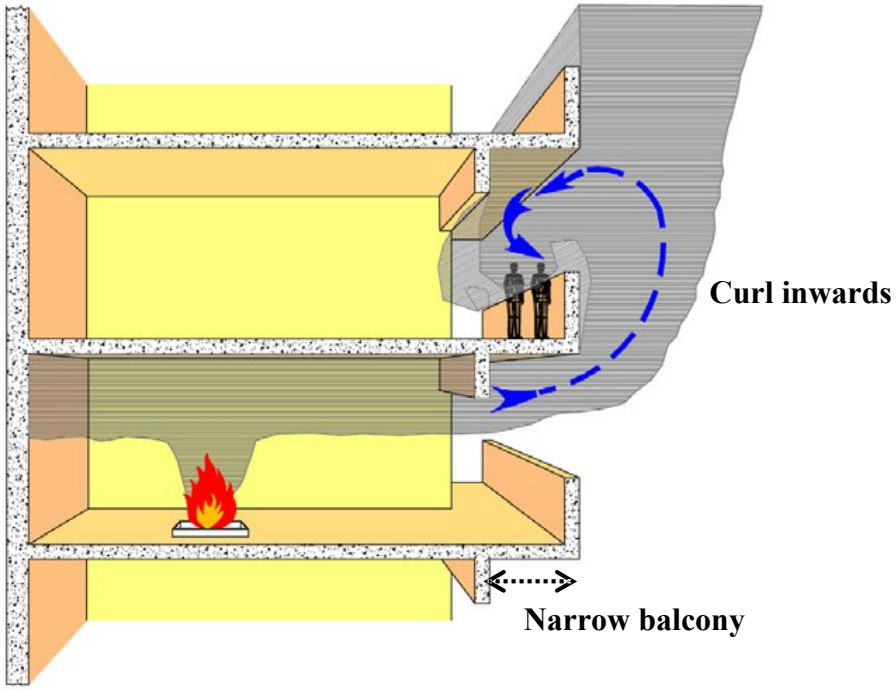

Figure 1-9: Balcony spill plume curls inwards towards the atrium structure [adapted from Morgan *et al* (1999)]

The factors affecting the behaviour of the balcony spill plume are not limited to the balcony breadth and the momentum of the spill plume. Admittedly, not all the factors are well investigated and wholly understood. The literature review in the next chapter will discuss some of these factors in greater detail.

1.2.3 Use of Channelling Screens

When the balcony spill plume flows beneath the balcony towards the balcony edge, the smoke will also flow sideways and cover a wider area along the balcony edge as shown by the arrows in Figure 1-10. This results in large amounts of air being entrained, and in turn results in a large volume of smoke entering the atrium space.

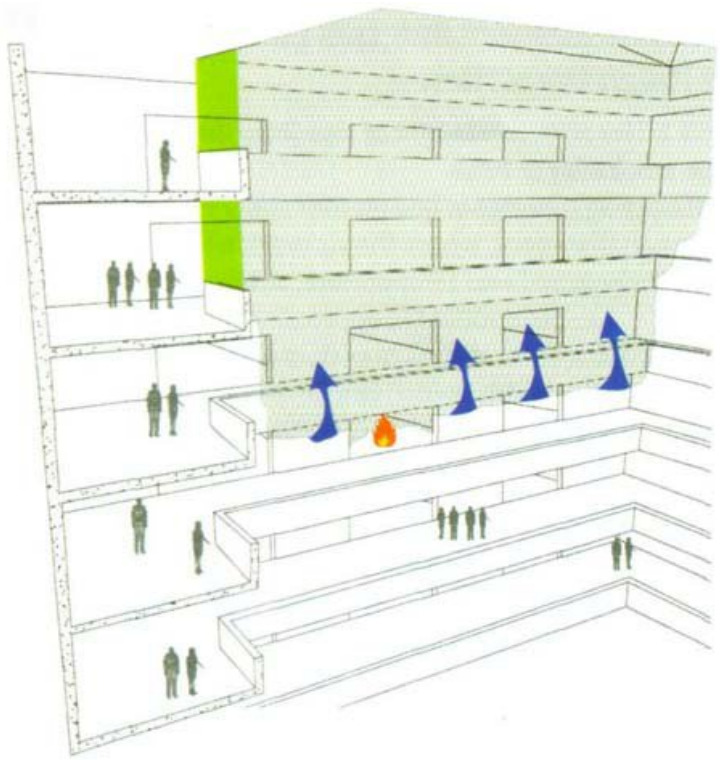

Figure 1-10: Smoke flowing sideways beneath a balcony [from Morgan *et al* (1999)]

Morgan *et al* (1999) recommends the use of channelling screens to restrict the lateral spread of smoke flowing beneath the balcony. By doing so, the volume of smoke entering the atrium space is reduced, leading to the reduction of smoke exhaust capacities. Typically, channelling screens extend from the opening of the fire compartment to the balcony edge and are aligned with the width of the opening. An example of the channelling screens is shown in Figure 1-11.

Although channelling screens may not be utilised as part of smoke management in atriums due to installation costs and design aesthetics, this research project is only concerned with balcony spill plumes that are channelled by channelling screens. For cases where the balcony spill plumes are unchannelled, current research work is being carried out by Tiong (2009) using computational fluid dynamics (CFD) simulations.

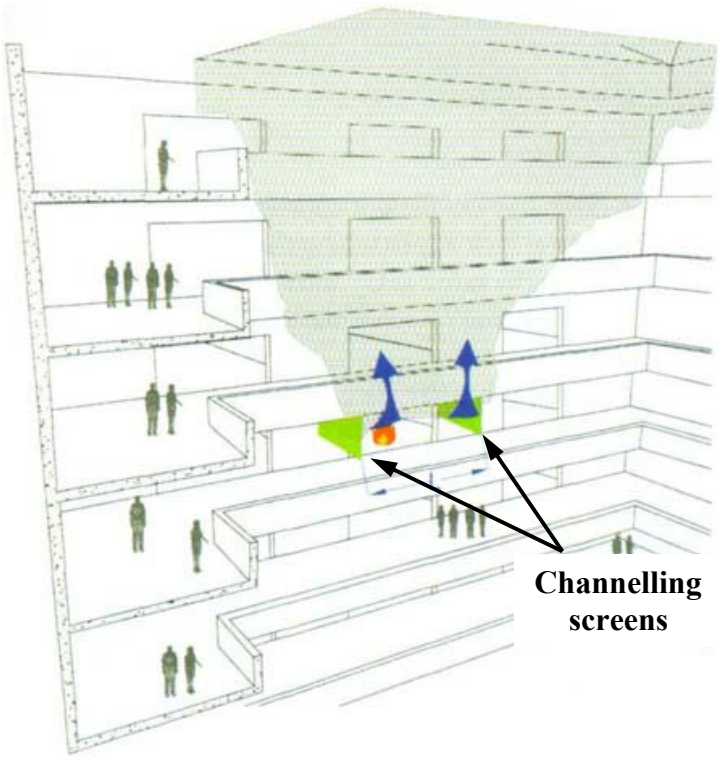

Figure 1-11: Channelling screens [adapted from Morgan *et al* (1999)]

1.3 Research Objective

Whether the balcony spill plume will rise as a free plume or curl inwards towards the atrium structure is of considerable concern to Fire Engineers in atrium design given that areas within the atrium may need to be kept tenable for safe evacuation of building occupants. In addition, it is expected that a spill plume that curls inwards towards the atrium structure will entrain less air, as compared to a free plume. As such, another interest to Fire Engineers is the design of related smoke management systems, given that the design of smoke management systems is directly related to the rate of air entrainment in an atrium.

There has been considerable research work on the balcony spill plume through experimental studies (Hansell *et al*, 1993; Harrison, 2004; Marshall & Harrison, 1996; Morgan & Marshall, 1975) and CFD modelling (Chow, 1998; Chow & Li, 2001; Miles *et al*, 1997). In addition, a number of standards and engineering guides on smoke management in atriums have been developed for Fire Engineers (Klote & Milke, 2002; Morgan *et al*, 1999; NFPA, 2005). However, most of the guidance on the balcony spill plume is concentrated on mass flow rate calculations. There exists limited guidance for Fire Engineers on the behaviour

of the balcony spill plume in an atrium. When taking into consideration the effects of various factors (e.g. balcony breadth, plume width and fire size), it is not known how the balcony spill plume will flow and where it will cause smoke contamination in the atrium.

The only relevant guidance is made available by Morgan *et al* (1999), that states "*balconies which are shallow (< 2 m) will cause the rising spill plume to curl inwards towards the structure…… smoke-logging the balcony levels above the fire floor*". This guidance is based on the smoke flow experiments conducted by Hansell *et al* (1993) in a model atrium. The number of experiments is limited and the results may not be robust. This results in the guidance being generic and does not specify whether it is applicable to a range of plume widths and fire sizes.

Hence, this research project is primarily a qualitative examination of the behaviour of the balcony spill plume in a fully open atrium. Its main objective is to systematically investigate the effects of varying balcony breadths, plume widths and fire sizes on smoke contamination in upper balconies through experimental work. The desired outcome of this research project is to provide improved guidance for Fire Engineers on the behaviour of the balcony spill plume in a fully open atrium with respect to smoke contamination in upper balconies.

2 LITERATURE REVIEW

This chapter provides a review of the research work by Hansell *et al* (1993). In addition, other relevant research work on factors affecting the behaviours of the balcony spill plume and thermal spill plume (without a balcony) in an atrium is included.

2.1 Hansell, Morgan and Marshall

A series of smoke flow experiments were conducted by Hansell *et al* (1993) using a one-tenth scale model of a 6-storey atrium building. The fire was simulated by a modified electric air heater, with the heating elements spatially distributed within the fire compartment. A balcony projected beyond the fire compartment opening, with the underside 10 mm above the compartment opening. A second balcony could be installed 0.5 m above the first balcony if desired. The balconies ran across the full width of the atrium. A schematic diagram of the experimental setup is shown in Figure 2-1.

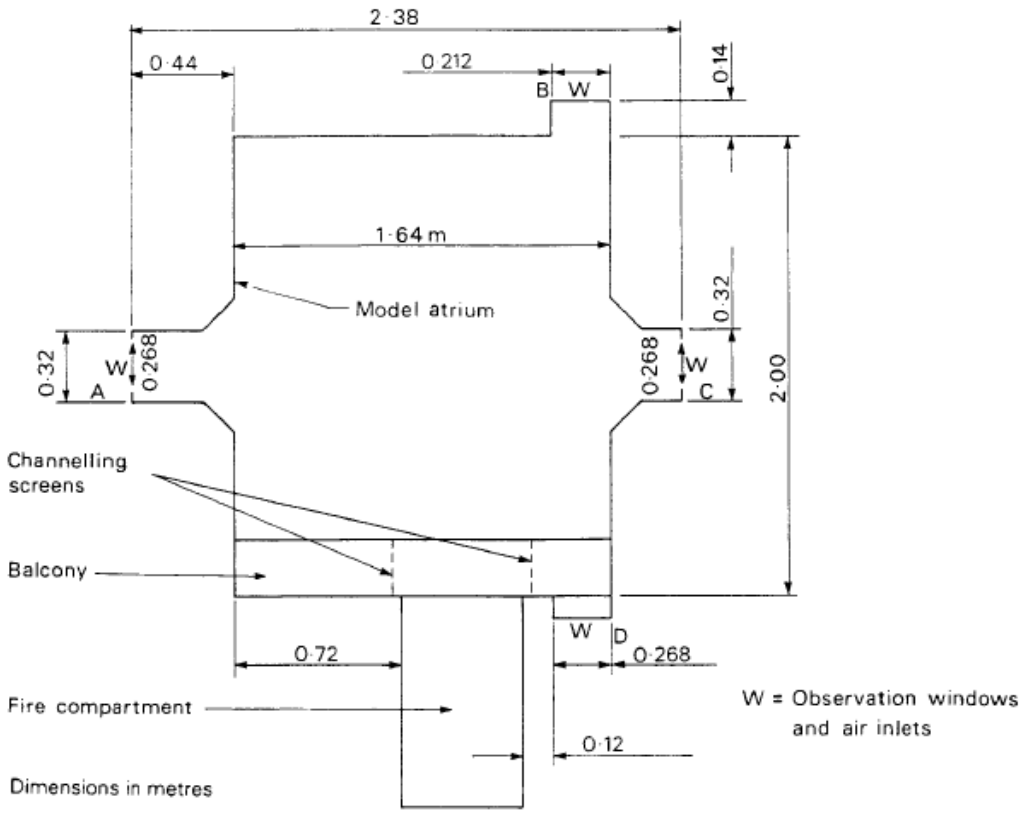

Figure 2-1: Plan of model atrium and fire compartment [from Hansell *et al* (1993)]

A total of 41 experiments were conducted by varying the balcony breadths and the number of heater banks. In some experiments, channelling screens were used and positioned at varying widths. Different experiments investigated different aspects of the balcony spill plume, such as the effective discharge coefficient at the spill edge, lateral spread beneath the balcony, plume re-attachment to atrium wall, smoke-logging on balconies and critical temperatures for entrainment calculations. Of relevance to this research project is smoke-logging on balconies. The term 'smoke-logging' conventionally refers to an extensive smoke layer from floor to ceiling, whereas the term 'smoke contamination' used in this report refers to any extent of smoke observed visually. As the term 'smoke-logging' was not defined by Hansell *et al* (1993), it is taken to be synonymous with the term 'smoke contamination' used in this report.

2.1.1 Plume Re-attachment to Atrium Wall

Thirteen experiments involving one balcony were conducted. The effect of balcony breadth on plume re-attachment to the atrium wall was investigated. Visual observations of the height above the balcony where the plume first touches the wall were recorded. The balcony breadths used for the experiments were 0.125 m, 0.25 m and 0.5 m. Channelling screens were used for balcony breadths of 0.125 m only. They were spaced 0.525 m apart, and were butted against both the fire compartment wall and the underside of the balcony.

No plume re-attachment was observed for the experiments involving balcony breadths of 0.25 m and 0.5 m. Plume re-attachment was observed for the experiments involving balcony breadth of 0.125 m. The re-attachment height increased with the number of heater banks. In addition, it was observed that there was reduced visibility in the space confined by the wall, the balcony and the plume. The experiment results are summarised in Table 2-1.

2.1.2 Smoke-logging on Balconies

A single experiment involving two balconies was conducted. Both balcony breadths were 0.125 m and no channelling screens were used. It was observed that most of the lower balcony was smoke-logged, while the upper balcony was entirely smoke-logged above its upper surface.

2.1.3 Experiment Conclusions

The experiment results concluded that for the balconies in an atrium to be kept clear of smoke, the balconies must be broader than 1.25 m (full scale) but not necessary to be broader than 2.5 m (full scale). It was suggested that 2 m (full scale) would be the appropriate minimum balcony breadth to meet the purpose of having balconies clear of smoke, i.e. smoke-logging can be expected for balcony breadths less than 2 m (full scale). In addition, if there were higher balconies, smoke-logging would be more extensive.

Table 2-1: Re-attachment height of plume (Hansell *et al*, 1993)

Experiment	Balcony Breadth (m)	Channelling Screens (m)	No. of Heater Banks	Lateral Width at Edge (m)	Re-attachment Height (m)
1	0.5	None	1	1.6	Not attached
2	0.5	None	2	1.6	Not attached
3	0.5	None	3	1.6	Not attached
4	0.25	None	1	1.6	Not attached
5	0.25	None	2	Not recorded	Not attached
6	0.25	None	3	0.8	Not attached
7	0.25	None	4	0.8	Not attached
8	0.125	None	1	0.8 – 1.0	0.15 ± 0.025
9	0.125	None	2	0.70 – 0.75	0.25 – 0.30
10	0.125	None	3	0.60 – 0.65	0.80 ± 0.025
11	0.125	0.525	1	0.525	0.25 – 0.30
12	0.125	0.525	2	0.525	0.60 – 0.70
13	0.125	0.525	3	0.525	0.90 – 1.0

Hansell *et al* (1993) showed that the extent of smoke contamination above the balcony was dependent on the balcony breadth. Apart from that, he suggested that the extent of smoke contamination was also dependent on the 'length of the line plume' (i.e. plume width), though no experiments were conducted to investigate this. Hence, it would be sensible to investigate systematically the collective effect of balcony breadth and plume width on smoke contamination in upper balconies.

2.2 Yii

A qualitative study on the balcony spill plume was conducted by Yii (1998) using salt water modelling and Laser Induced Fluorescence flow visualisation technique. A one-twentieth scale model was used to conduct a series of salt water experiments, as shown in Figure 2-2. Four experiments were conducted with two spilling densities of 0.5 % and 1 % of salt (by weight) and two balcony breadths of 0.125 m and 0.25 m (Table 2-2).

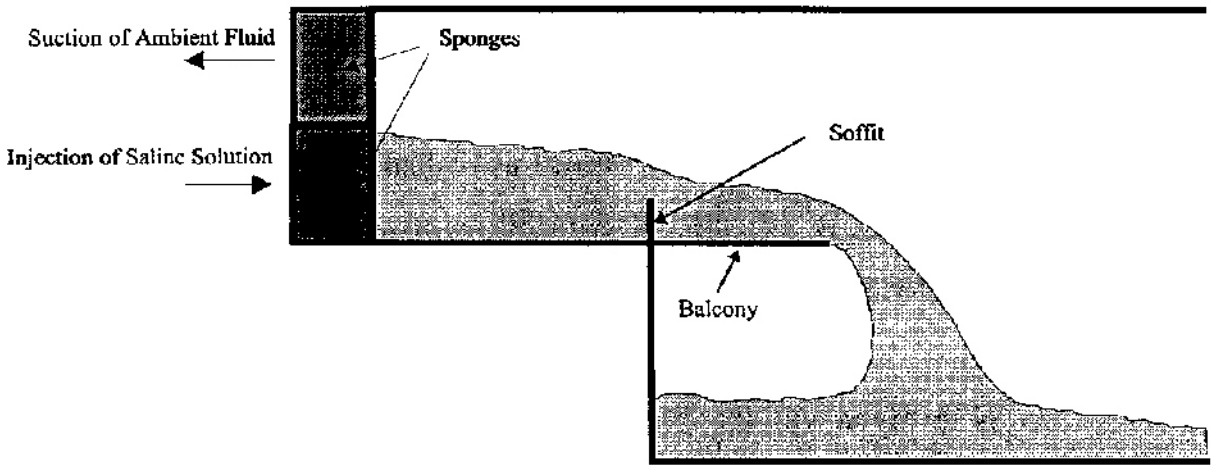

Figure 2-2: Schematic diagram of salt water modelling experiment [from Yii (1998)]

Table 2-2: Series of experiments by Yii (1998)

Experiment	Spill Density (%)	Balcony Breadth (m)
SP-B01	0.5	0.125
SP-B02	1.0	0.125
SP-C01	0.5	0.250
SP-C02	1.0	0.250

Smoke-logging in the balcony was found to be more severe for the shorter balcony in comparison to the longer balcony. As the term ‘smoke-logging’ was not defined by Yii (1998), it is taken to be synonymous with the term ‘smoke contamination’ used in this report. The experiment results also suggested that there was dependence between the fire heat release rate and the smoke layer depth beneath the balcony. In turn, this would affect the

trajectory of the balcony spill plume, as shown in Figure 2-3. However, further research was desired, given the limited number of experiments conducted.

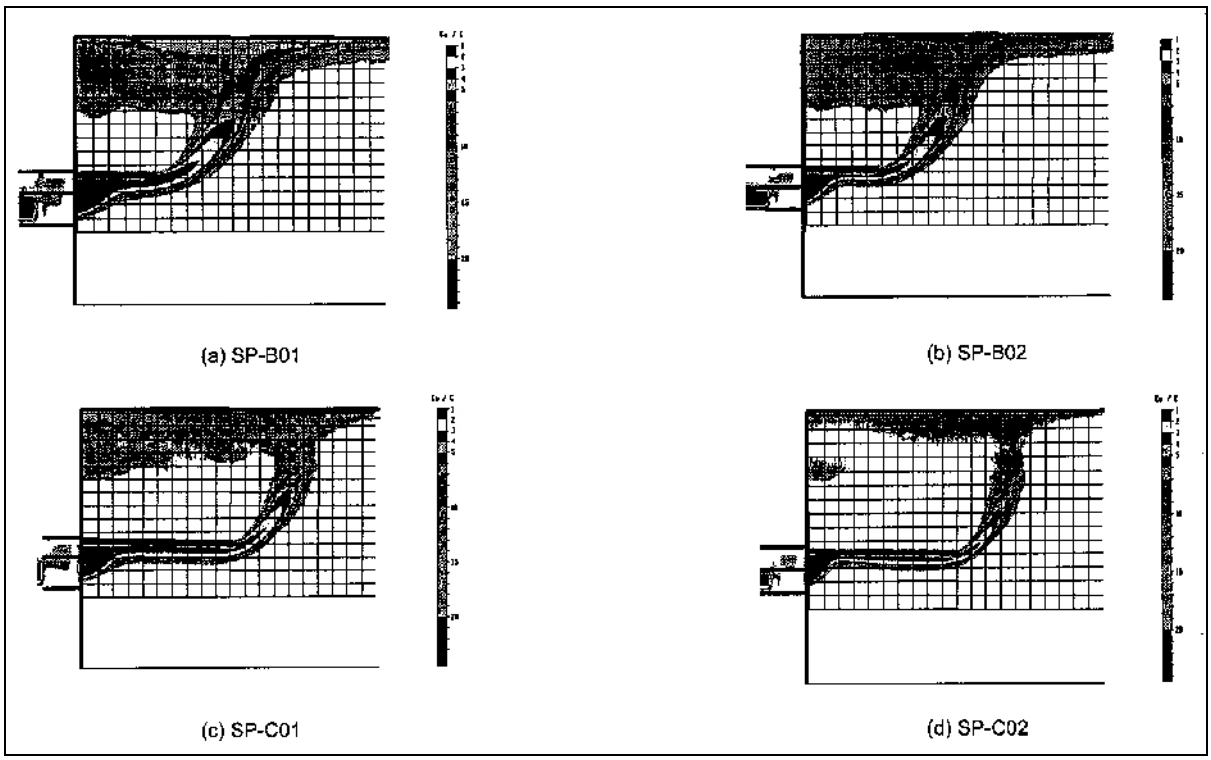

Figure 2-3: Plots of flow images for experiments [from Yii (1998)]

Despite the limited number of experiments, Yii's (1998) findings serve to reinforce the conclusions by Hansell *et al* (1993) mentioned in the preceding section. That is, the effect of balcony breadth on smoke contamination above the balcony. In addition, the findings would suggest that the effect of fire heat release rate should be investigated in conjunction with that of balcony breadth and plume width.

2.3 Harrison

Harrison (2004) performed a number of CFD simulations using Fire Dynamics Simulator to investigate the flow of a balcony spill plume from a compartment opening to a higher projecting balcony. The simulation models were based on a one-tenth scale model of an atrium and a fire compartment, as shown in Figure 2-4.

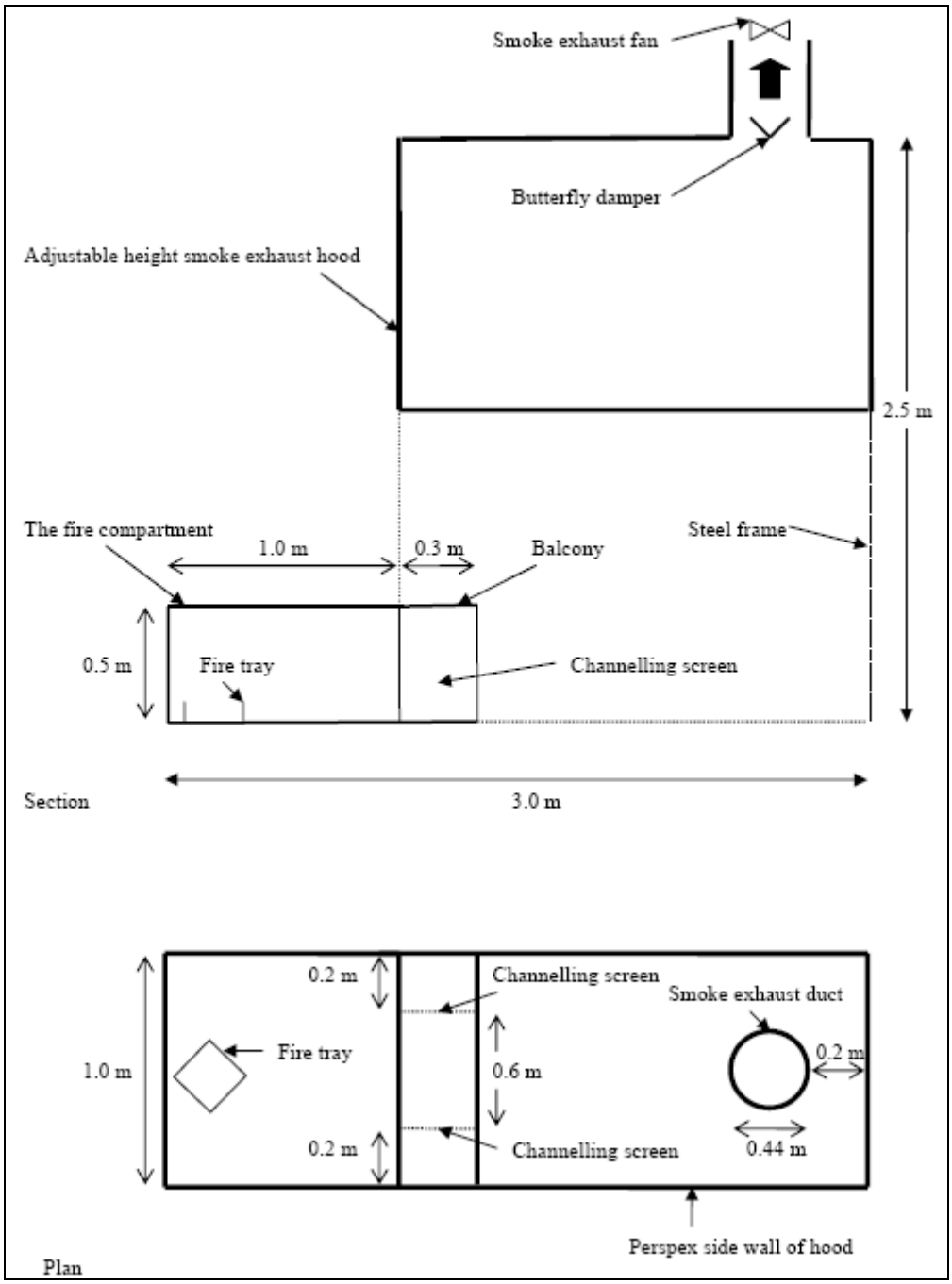

Figure 2-4: Schematic of one-tenth scale model [from Harrison (2004)]

A single balcony of 0.3 m breadth projected from the fire compartment. There was a downstand of 0.2 m at the opening of the compartment. Channelling screens were placed at the sides of the compartment. Two widths of compartment openings were used, namely 0.2 m and 1.0 m. It was found that the flow of the balcony spill plume had an increased amount of

horizontal projection from a narrow opening as compared to a wide opening, as shown in Figure 2-5 and Figure 2-6.

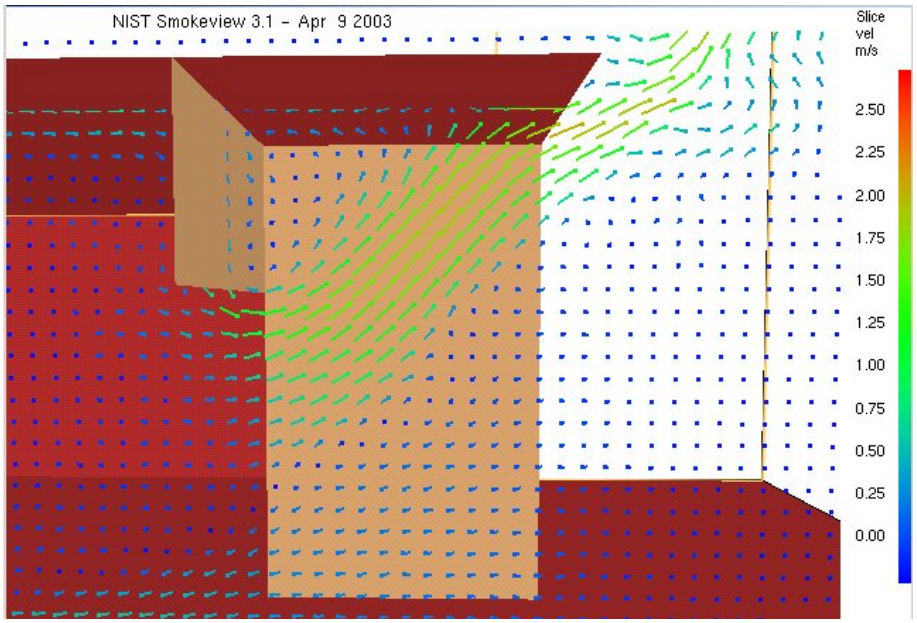

Figure 2-5: Velocity vectors for narrow opening [from Harrison (2004)]

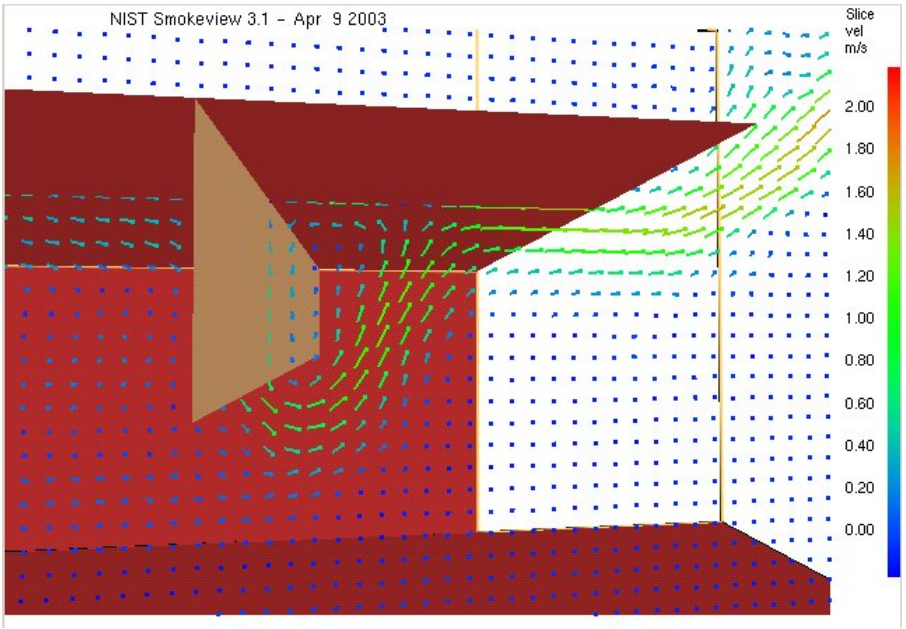

Figure 2-6: Velocity vectors for wide opening [from Harrison (2004)]

Though only two widths of compartment openings were used, the findings by Harrison (2004) serve to reinforce the suggestion by Hansell *et al* (1993), that the extent of smoke

contamination above the balcony may be dependent on the plume width. There is a need to investigate this issue with a wider range of plume widths.

2.4 Yokoi

A series of small scale experiments were conducted by Yokoi (1960) for hot fire gases issuing from windows. The experiments involved a model room with varying aspect ratios of the width of window to the height of window, as shown in Figure 2-7. There was a vertical wall above the window opening. Unlike the preceding sections of research work, the experiments did not involve any balconies.

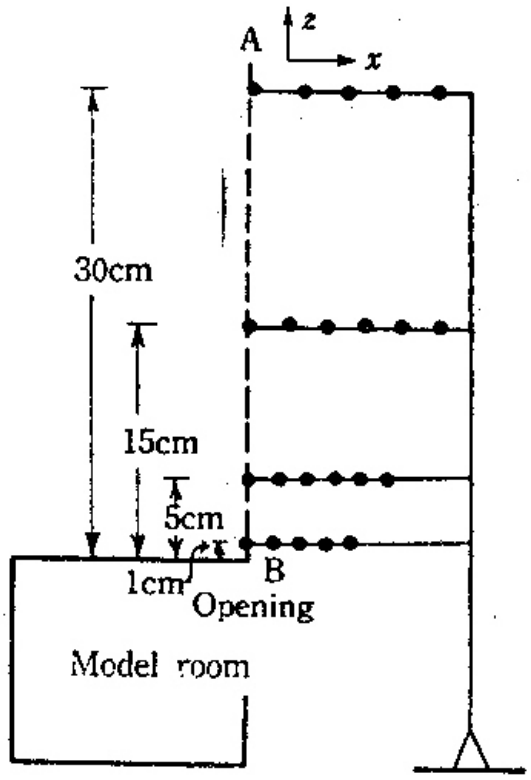

Figure 2-7: Schematic diagram of model room [from Yokoi (1960)]

The aspect ratios of twice the width of window to the height of window used in the experiments are summarised in Table 2-3. It is important to note that as the experiments involved a room fully involved in fire, the depth of the thermal spill plume flowing out of the window is approximately half of the window height. Hence, the aspect ratio is approximately the ratio of the width of window to the depth of spill plume.

Table 2-3: Summary of aspect ratios in Yokoi's (1960) experiments

Experiment	Aspect Ratio
a	Not applicable
b	1.0
c	1.5
d	2.0
e	2.5
f	3.0
g	3.4
h	6.4

From the experiment results, it was noted that the aspect ratio of the window had a strong influence on the behaviour of the thermal spill plume rising out of the window. When the width of window was narrow in comparison to its height, the trajectory of the spill plume was such that it would project further out before 'rotating' and rising vertically due to buoyancy (e.g. Experiment b). On the other hand, when the width of window was wide in comparison to its height, the trajectory of the spill plume was such that it would 'rotate' quickly and attach itself to the surface of the vertical wall above the window opening (e.g. Experiment h). The experiment results for the trajectories of the spill plume are shown in Figure 2-8.

Yokoi's (1960) findings showed that the depth of smoke layer flowing out of the fire compartment would have some bearing on the trajectory of the thermal spill plume. Therefore, it would suggest that the depth of smoke layer would have an effect on smoke contamination in upper balconies for the case of a balcony spill plume. This would not be unusual given that the depth of smoke layer is dependent on both fire heat release rate and plume width (Hansell, 1993; Morgan *et al*, 1999). By investigating the collective effect of fire heat release rate and plume width, the effect of the depth of smoke layer would be accounted for.

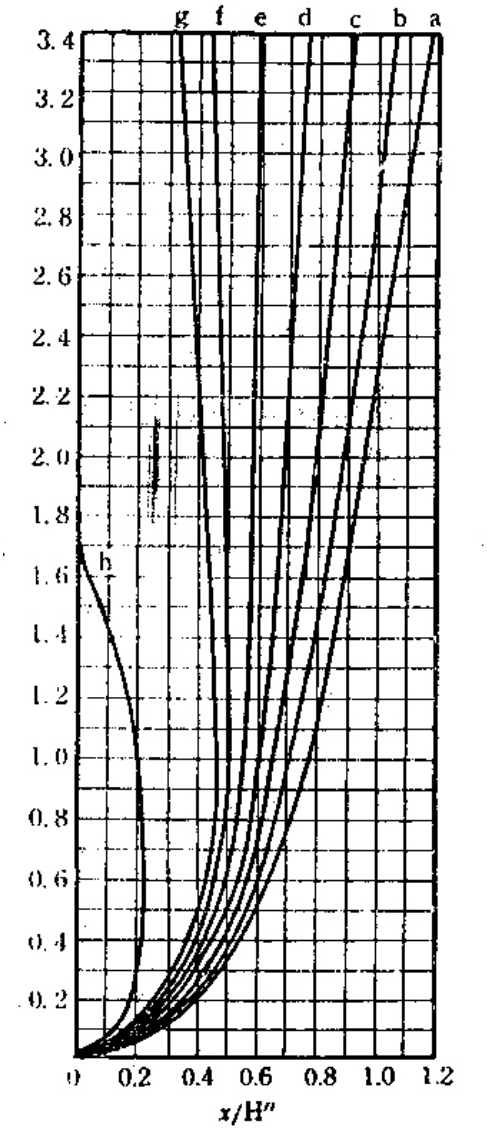

Figure 2-8: Trajectories of hot gases ejected from various windows [from Yokoi (1960)]

2.5 Poreh

A series of experiments were conducted by Poreh *et al* (2008) using a model of a large hall, as shown in Figure 2-9. The experiments investigated the effect of the Froude number, *Fr* on the behaviour of the thermal spill plume, in particular the adherence of the spill plume to a vertical wall above the spill edge. Similar to Yokoi's (1960) research work, there were no balconies.

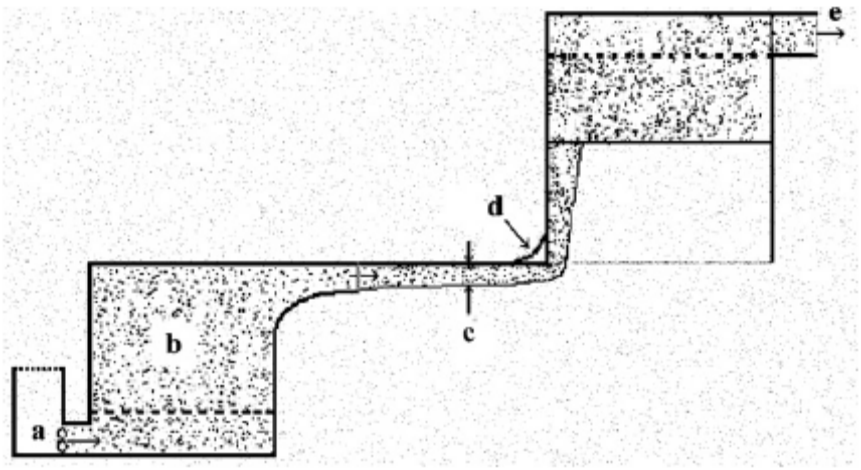

Figure 2-9: Schematic diagram of the Froude number experiments: a – hot smoke generator; b – chamber for smoke distribution; c – location of measurements; d – curved corner for 2nd set of experiments; e – exit [from Poreh *et al* (2008)]

It was shown that the initial shape of the rising plume in the atrium was dependent on *Fr* of the horizontal smoke layer upstream of the spill edge. When $Fr < 1$, the plume would immediately adhere to the atrium wall. However, when $Fr > 1$, the smoke layer may not adhere to the atrium wall and would start rising up as a free plume.

For the experiments, the *Fr* of the horizontal smoke layer was changed by varying the fire heat release rate. From the findings by Poreh *et al* (2008), it would suggest that the extent of smoke contamination in upper balconies for the case of a balcony spill plume would be dependent on the fire heat release rate. Again, this was consistent with previous research work mentioned in the preceding sections.

3 METHODOLOGY

In this chapter, the methodology – approach, experiment apparatus, instrumentation, experiment variables and procedure, adopted for this research project is described. The methodology was similar to complementary research work on entrainment mechanisms of the thermal spill plume by Harrison (2009). In particular, the approach and experiment apparatus were kept generally the same, so that the calibration and experiment results (e.g. fire heat release rates and compartment flows) could be used for this research project.

3.1 Approach

This research project adopted the approach of physical scale modelling, in the form of burning fires in a reduced physical scale model. The physical scale model enables an effective way of investigating and visualizing smoke movement without the need for full scale experiments.

3.1.1 Turbulent Flows

In order for the experiment results to be extrapolated from model scale to full scale, the scaling laws set out by Thomas *et al* (1963) had to be met. Essentially, this was a modified Froude number, *Fr* scaling and required the equivalent flows on both the full and model scales to be fully turbulent, i.e. the Reynolds number, *Re* of significant flows should exceed the critical value of 4000 (Massey, 1990).

In the experiments from complementary research work by Harrison (2009), the *Re* for the typical flows from the fire compartment were calculated using:

$$Re = \frac{ul}{v} \tag{1}$$

The calculated *Re* ranged between 8,100 and 20,400. It was established that the flows were fully turbulent and that any scaling laws could be applied with confidence. Hence, identical compartment flows were used in this research project

3.1.2 Scaling Laws

Dimensional relationships between fluid dynamics variables were derived from first principles by Morgan *et al* (1976). An elaboration of the derivation process can be found in Harrison (2009). By holding certain variables constant, the relationships can be simplified to obtain the required scaling laws.

For this research project, when the temperature above ambient was kept constant, the scaling laws became:

$$\dot{Q}_c \propto L^{5/2}$$
$$\dot{m} \propto L^{5/2}$$
$$\dot{V} \propto L^{5/2}$$
$$u \propto L^{1/2} \quad (2)$$

As an example, if the length scale, L is changed by a factor of 10, the convective heat release rate scale, $\dot{Q}_c$ will change by a factor of 316. As the scaling laws do not apply to conductive and radiative heat transfer processes, it is assumed that the heat transfer mechanisms in this research project were pre-dominantly convective.

3.2 Physical Scale Model

A one-tenth physical scale model representing a six-storey atrium building was designed and constructed (schematic diagrams shown in Figure 3-1), similar to that used by Harrison (2009). The scale model simulated a fire in an adjacent compartment connecting a fully open atrium. It consisted of two main compartments, namely the fire compartment (as an adjacent compartment) and the atrium.

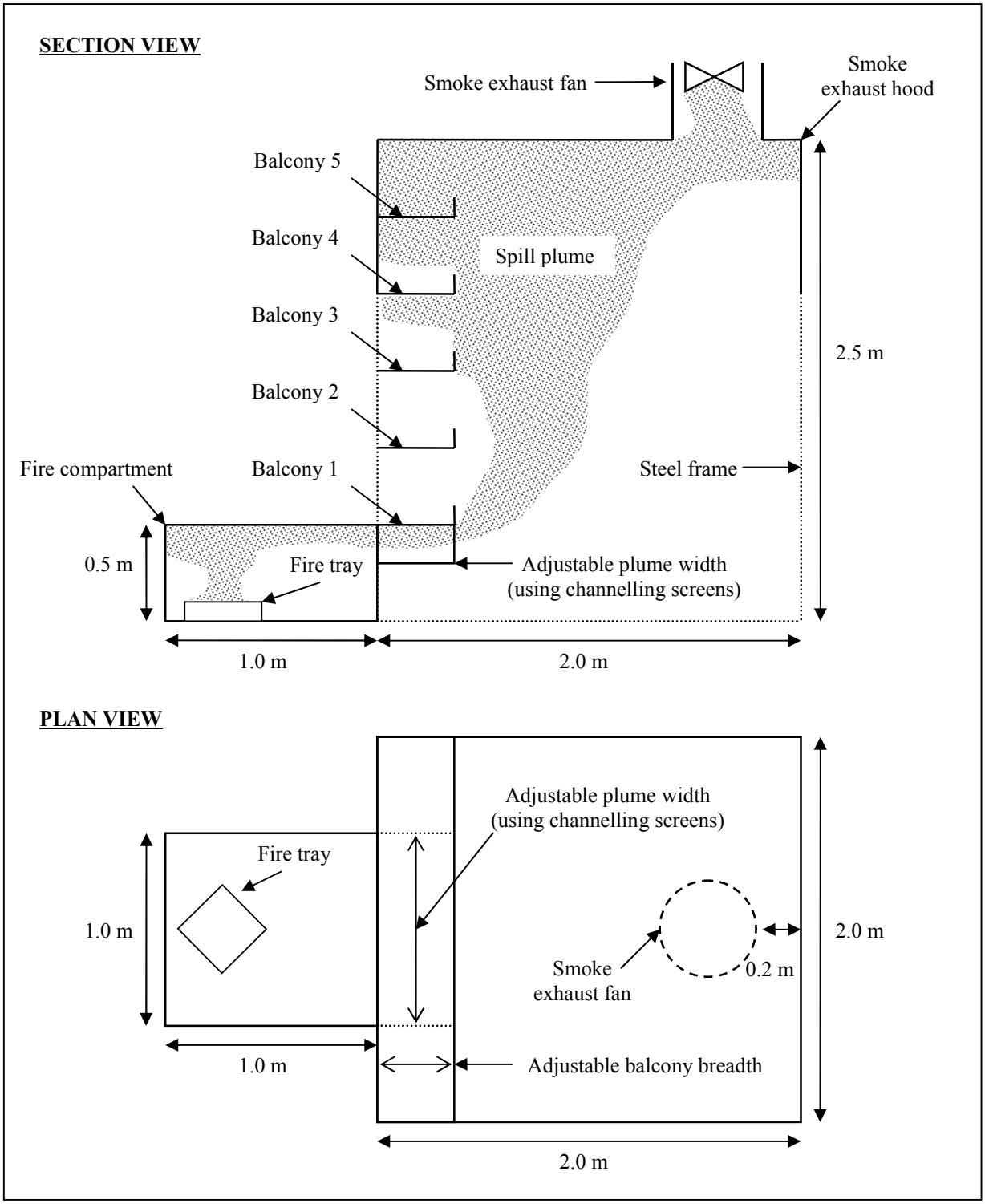

Figure 3-1: Schematic diagram of physical scale model

3.2.1 Fire Compartment

The fire compartment of internal dimensions 1 m by 1 m by 0.5 m high was constructed from 1 mm thick steel sheets. The internal surfaces were protected by 25 mm thick Ceramic Fibre Insulation (CFI) boards. The width of the compartment opening could be varied using 'inserts' that were constructed similarly (Figure 3-2).

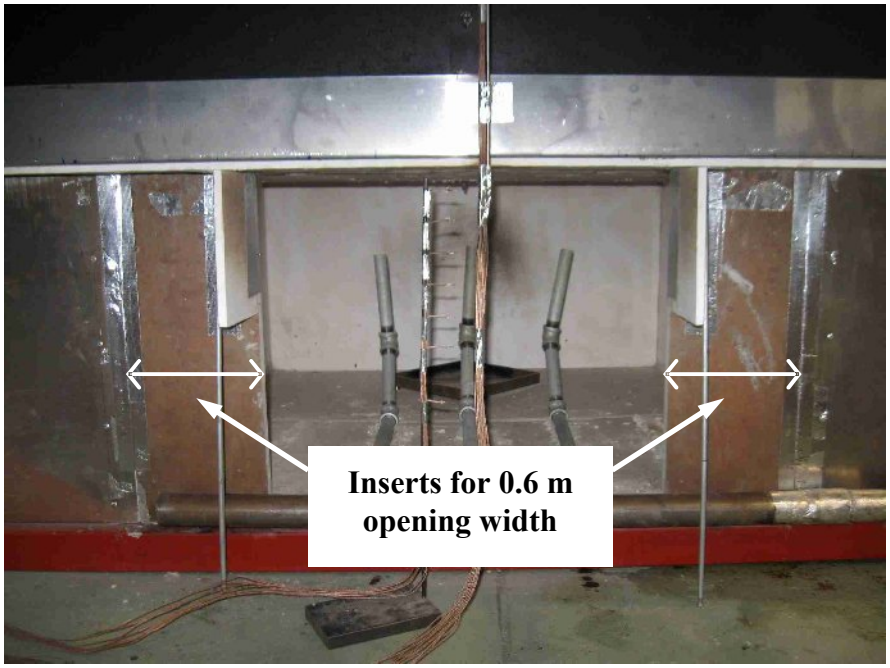

Figure 3-2: Fire compartment with inserts for 0.6 m opening width

3.2.2 Fire Source

The fire was generated by supplying and burning Industrial Methylated Spirit (IMS) fuel at a steady rate in a steel tray (Figure 3-3). The fuel was supplied to the steel tray from a fuel reservoir via a flowmeter (Figure 3-4). The steel tray, measuring 0.25 m by 0.25 m by 0.015 m high, was positioned at the rear of the fire compartment and tilted slightly to allow the fuel surface to be reasonably uniform. This ensured that the burning rate matched the inflow of the fuel.

Figure 3-3: Fire source

Figure 3-4: Fuel reservoir (left) and flowmeter (right) for IMS fuel

Based on the properties of the IMS fuel, the total fire heat release rate, $\dot{Q}_T$ was calculated from heat of combustion, density and volume flow rate through the flowmeter, using:

$$\dot{Q}_T = c_{IMS} \rho_{IMS} \dot{V}_{IMS} \tag{3}$$

The calibration of the required volume flow rate through the flowmeter to the total fire heat release rate was conducted by Harrison (2009). As the same flowmeter was used for this research project, the calibrated results were used.

3.2.3 Atrium

The atrium was of internal dimensions 2 m by 2 m by 2.5 m high (Figure 3-5). The main supporting frame of the atrium was constructed using steel sections. Three out of the four vertical faces of the atrium were side walls constructed from 2 mm thick steel sheets and affixed to the supporting steel frame. The internal surfaces of the side walls were protected by 10 mm thick CFI boards. The side walls were constructed such that they could move freely in the vertical direction along the supporting steel frame.

Figure 3-5: Atrium

The fourth vertical face of the atrium was kept free of obstructions to allow for visual observations. However, due to the need to contain and exhaust the hot smoke properly, the top

portion of this vertical face was partially covered by a side wall constructed from 12 mm thick Perspex sheet. This created an exhaust hood that enabled the hot smoke to be contained and exhausted via a mechanical fan. The mechanical fan was a 0.44 m diameter bifurcated fan attached to the exhaust hood vent using temperature resistant flexible ducting. The fan speed was controllable, enabling different exhaust rates.

In order to enhance the visual observations, the internal of the atrium was painted with a black background and a luminous mesh of grid size 75 mm by 75 mm was installed as a visual guide (Figure 3-6).

Figure 3-6: Black background and luminous grid mesh

3.2.4 Balconies

The atrium housed five levels of balconies above the opening of the fire compartment. The balconies were designed with 0.1 m high upstands and were constructed from 1 mm thick steel sheets (Figure 3-7). The height of 0.1 m represented a typical approved height for safety

barriers (BCA, 2008). In order to minimise heat losses and enable scaling, the underside of Balcony 1 was further protected with 10 mm thick CFI boards. This was consistent with the research work of Harrison (2009).

Figure 3-7: Balconies with 0.1 m high upstands

The underside of Balcony 1 was flush with the top of the opening of the fire compartment. The subsequent balconies above were positioned 0.4 m vertically apart (from floor to floor). In theory, the balconies could be positioned apart for a range of heights. However, the height of 0.4 m was chosen as an appropriate typical representation of a full scale balcony spacing of 4 m. The balconies occupied the full 2 m width of the atrium, while the balcony breadth was made adjustable (as an experiment variable). A schematic diagram of the balcony dimensions is shown in Figure 3-8.

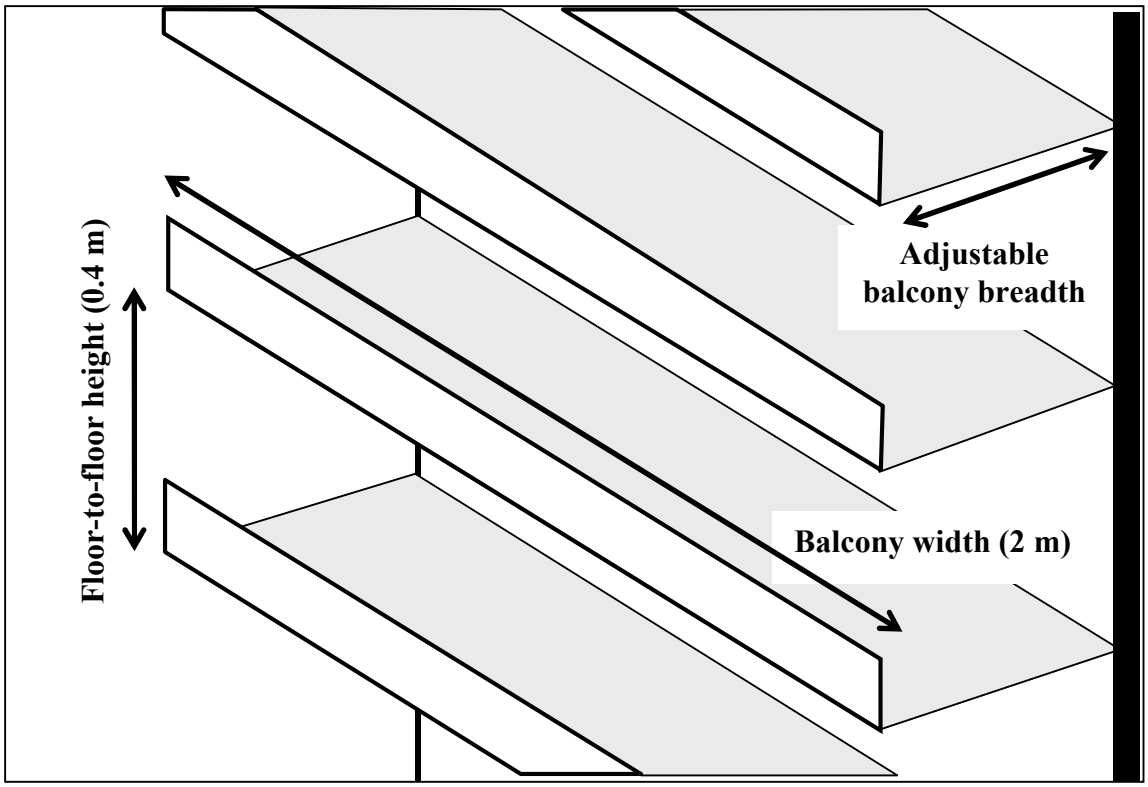

Figure 3-8: Schematic diagram of the balcony dimensions

3.2.5 Channelling Screens

Channelling screens were constructed from 1 mm thick steel sheets and protected with 10 mm thick CFI boards. The screens were 0.2 m deep and occupied the full breadth of Balcony 1. The screens were designed such that the smoke flowing beneath Balcony 1 was contained within the depth of the screens. The screens were butted to the underside of Balcony 1 and the atrium wall (that the balconies were attached to), and were aligned with the width of the opening of the fire compartment. This ensured that the plume width (that is parallel to the edge of Balcony 1) followed the width of the opening. An example of the channelling screens used in the experiments is shown in Figure 3-9.

Figure 3-9: Channelling screens

3.3 Instrumentation

3.3.1 Flow Visualisation

Visual observations and photography of the experiments were carried out. The primary interests were the behaviour of the balcony spill plume and the extent of smoke contamination in upper balconies. As the IMS fuel burns with no visible smoke, commercial oil-mist smoke was introduced into the hot fire gases to enable visual observations and photography of the buoyant smoke flows. The oil-mist smoke was produced from a smoke generator and supplied through pipes as shown in Figure 3-10. The amount of oil-mist smoke to be introduced into the hot fire gases was manually controlled so that the visual observations would not be affected by any excessive oil-mist smoke.

Figure 3-10: Commercial smoke generator (left) and supply pipes (right) for oil-mist smoke

3.3.2 Smoke Temperatures

Smoke temperatures were measured to support the visual observations. The smoke temperatures were measured using 0.5 mm diameter exposed chromel/alumel (K-type) thermocouples, and the temperature readings were scanned at a rate of 1 reading/s and recorded using a data logging software. Three thermocouple columns were set up and positioned at various locations (schematic diagram in Figure 3-11).

The details and spacing of the thermocouples were as follows:

(i) Column A – A 9-thermocouple column running vertically from the edge of Balcony 1 to the base of the atrium (Figure 3-12). The column was centrally positioned along the balcony length and the thermocouples were spaced in accordance to Table 3-1. The thermocouples measured the smoke temperatures flowing out of the opening of the fire compartment. The temperature readings were monitored for stability of the experiments.

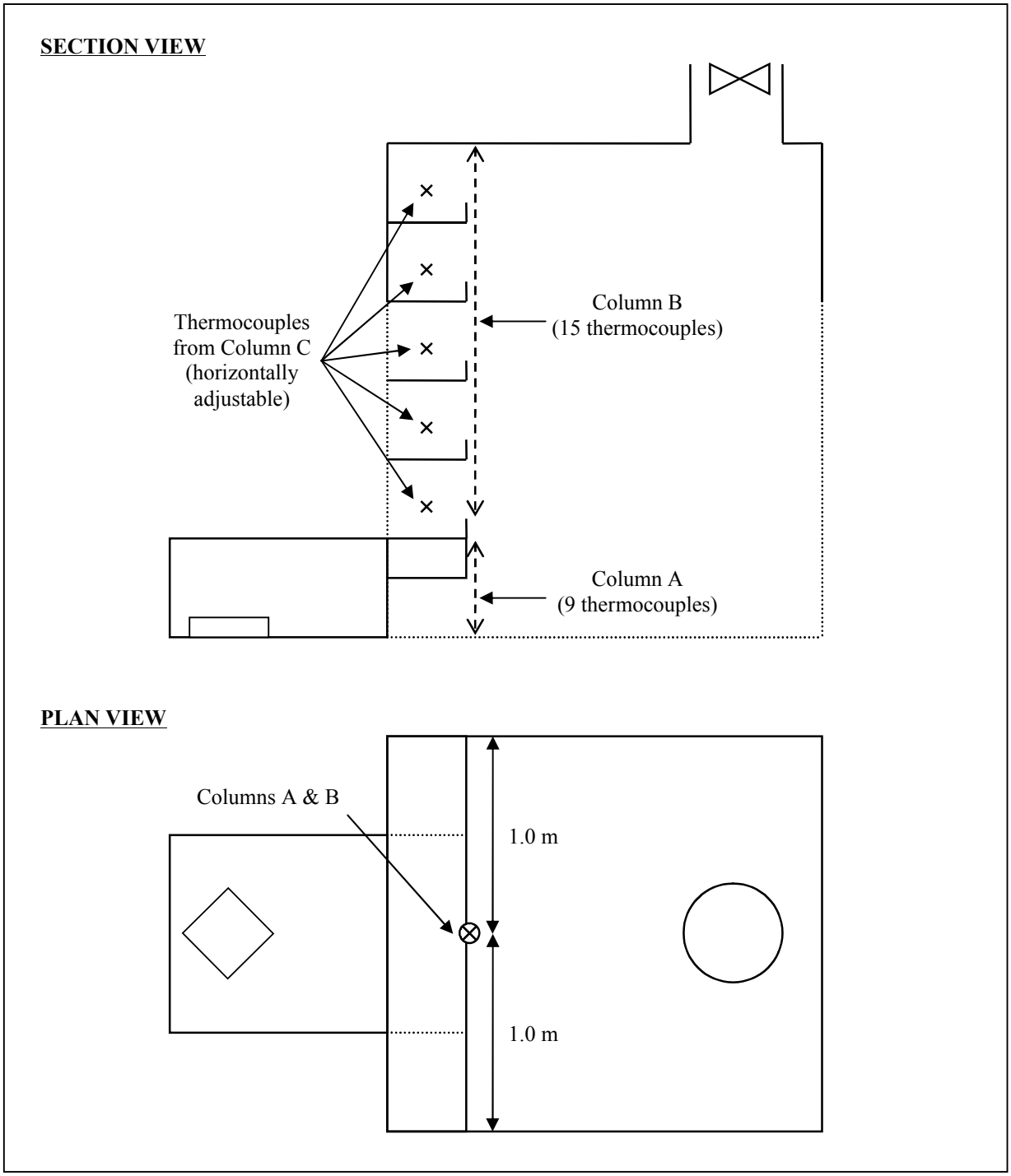

Figure 3-11: Locations of thermocouple columns

Figure 3-12: Column A with 9 thermocouples

Table 3-1: Spacing of thermocouples along Column A

Column	Number	Distance below edge of Balcony 1 (m)
A	1	0.03
	2	0.07
	3	0.11
	4	0.15
	5	0.19
	6	0.23
	7	0.30
	8	0.40
	9	0.50

(ii) Column B – A 15-thermocouple column running vertically from the edge of Balcony 1 to the ceiling of the atrium (Figure 3-13). The column was centrally positioned along the balcony length and the thermocouples were spaced in accordance to Table 3-2, whereby a set of three thermocouples were assigned to each balcony. The thermocouples measured the smoke temperatures flowing into the balconies. The temperature readings were analysed to determine the temperature profiles of any hot smoke flowing into the balconies.

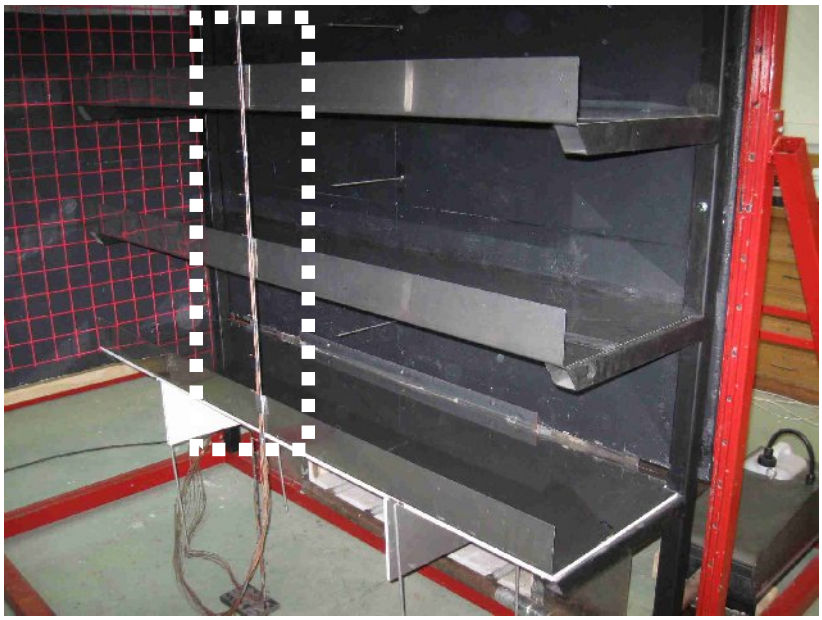

Figure 3-13: Column B with 15 thermocouples

Table 3-2: Spacing of thermocouples along Column B

Column	Number	Balcony	Distance above edge of Balcony Level 1 (m)
B	1	1	0.1
	2		0.2
	3		0.3
	4	2	0.5
	5		0.6
	6		0.7
	7	3	0.9
	8		1.0
	9		1.1
	10	4	1.3
	11		1.4
	12		1.5
	13	5	1.7
	14		1.8
	15		1.9

(iii) Column C – A 5-thermocouple column with one thermocouple located between balconies (Figure 3-14). Each thermocouple was positioned at 0.2 m above the balcony floor. The height of 0.2 m in model scale is equivalent to 2 m in full scale, and is a typical representation of head height (Spearpoint, 2008). The column was constructed such that the measuring end of the thermocouples could slide along the balcony breadth. This enabled measurement of smoke temperatures within the balconies at the desired points from the atrium wall (that the balconies were attached to). The measuring points for each balcony breadth are shown in Table 3-3. The temperature readings were analysed to determine the temperature profiles of the hot smoke layer within the balconies at the height of 0.2 m.

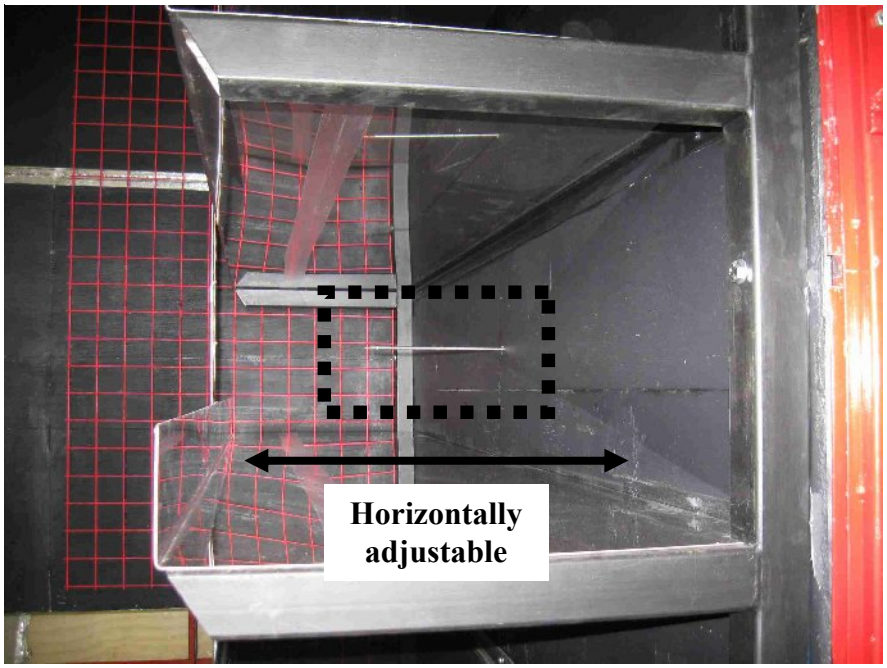

Figure 3-14: Column C with 1 thermocouple between balconies

Table 3-3: Measuring points for Thermocouple Column C

Balcony Breadth (m)	Distance from Atrium Wall (m)	
	Measuring Point 1	Measuring Point 2
0.50	0.25	0.05
0.30	0.15	0.05
0.20	0.10	0.05
0.15	0.05	Not Applicable

3.4 Experiment Variables

The main objective of this research project is to examine the various factors that may affect the behaviour of the balcony spill plume and the extent of smoke contamination in upper balconies. Three experiment variables were selected, namely balcony breadth, plume width and fire size.

3.4.1 Balcony Breadth

Four balcony breadths of 0.15 m, 0.2 m, 0.3 m and 0.5 m were used, and were equivalent to 1.5 m, 2 m, 3 m and 5 m on a full scale respectively. The range of 0.15 – 0.5 m was chosen in relation to real balcony designs, where a balcony breadth of less than 0.15 m is not practical and a balcony breadth of more than 5 m might be considered as a separate room or an intermediate floor. The balcony breadths were specifically selected so that some form of comparison could possibly be made with the findings from Hansell *et al* (1993) that 2 m would be the appropriate minimum balcony breadth.

3.4.2 Plume Width

Five plume widths of 0.2 m, 0.4 m, 0.6 m, 0.8 m and 1.0 m were used, and were equivalent to 2 m, 4 m, 6 m, 8 m and 10 m on a full scale respectively. These widths were considered typical of compartment openings, such as for shops and offices.

3.4.3 Fire Size

Three fire sizes of heat release rates 5 kW, 10 kW and 15 kW were used, and were approximately equivalent to 1.6 MW, 3.2 MW and 4.8 MW on a full scale respectively. The fire heat release rates were consistent with the range of design fires in an atrium recommended by Morgan *et al* (1999) and corresponded to those used by Harrison (2009).

3.5 Experiment Procedure

By configuring the three variables, a total of 60 experiments (Table 3-4) were conducted to characterise the behaviour of the balcony spill plume.

Table 3-4: Series of experiments with varying balcony breadths, plume widths and fire sizes

Experiment	Balcony Breadth, b (m)	Plume Width, w (m)	Heat Release Rate, Q_T (kW)
1	0.50	1.0	5
2			10
3			15
4		0.8	5
5			10
6			15
7		0.6	5
8			10
9			15
10		0.4	5
11			10
12			15
13		0.2	5
14			10
15			15
16	0.30	1.0	5
17			10
18			15
19		0.8	5
20			10
21			15
22		0.6	5
23			10
24			15
25		0.4	5
26			10
27			15
28		0.2	5
29			10
30			15
31	0.20	1.0	5
32			10
33			15
34		0.8	5
35			10
36			15
37		0.6	5
38			10
39			15
40		0.4	5
41			10
42			15
43		0.2	5
44			10
45			15
46	0.15	1.0	5
47			10
48			15
49		0.8	5
50			10
51			15
52		0.6	5
53			10
54			15
55		0.4	5
56			10
57			15
58		0.2	5
59			10
60			15

For each experiment, the procedure was as follows:

(i) Set up the required experiment variables, e.g. balcony breadth and plume width;
(ii) Set the nominal smoke exhaust extraction rate;
(iii) Supply the required fuel flow;
(iv) Ignite the fuel;
(v) Monitor the thermocouples in Column A;
(vi) Allow the temperature readings to reach stability;
(vii) Switch on the smoke generator;
(viii) Adjust the smoke exhaust extraction rate to keep smoke layer within the smoke exhaust hood;
(ix) Carry out visual observations and photography of the behaviour of the balcony spill plume;
(x) Switch off the smoke generator;
(xi) Scan all thermocouples and record the temperature readings for a period of 60 s.

A level of stability was considered to have been reached when temperatures fluctuated within a range of 5 °C. To illustrate, the stable temperature readings from Thermocouples A1, A2 and A3 in Column A were plotted against time for Experiment 1 in Figure 3-15.

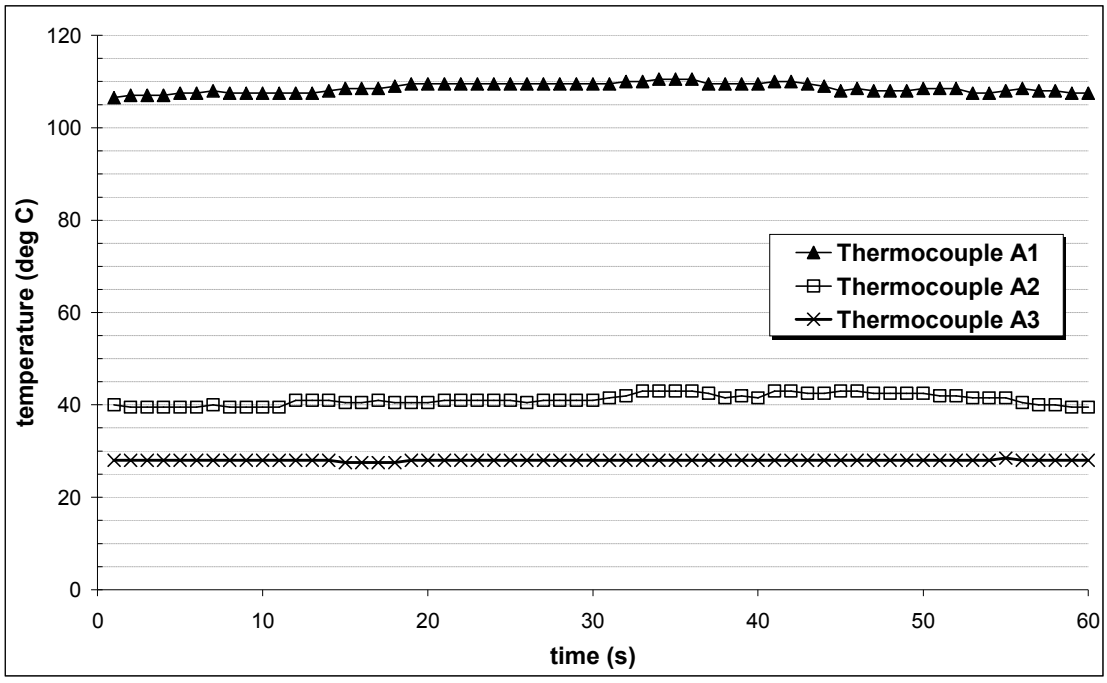

Figure 3-15: Temperature readings from Thermocouple Column A for Experiment 1

4 RESULTS

In this chapter, the experiment results for visual observations and temperature readings are presented. However, the scope will be limited to Balconies 1, 2 and 3. The reason for this limitation is the interference caused by a smoke layer within the exhaust hood of the atrium. As there was the need to contain and exhaust the hot smoke properly for health and safety reasons, the top portion of the atrium was enclosed by side walls to form an exhaust hood. During the experiments, the smoke would be contained within the exhaust hood and exhausted via a mechanical fan. At steady state conditions, a smoke layer would develop within the exhaust hood. As Balconies 4 and 5 were also enclosed within the exhaust hood, the smoke layer would contaminate Balconies 4 and 5, and affect the temperature readings.

4.1 Visual Observations of Balcony Spill Plume

This section describes the behaviour of the balcony spill plume as visually observed in the experiments. Three generic types of plume behaviour were observed and described as:

(i) Free plume;
(ii) 'Re-attached' plume; and
(iii) 'Adhered' plume.

The phenomenon of a 'secondary' balcony spill plume is also discussed.

4.1.1 Free Plume

It was generally observed that for experiments with broad balconies and narrow plume widths, the balcony spill plume flowing beneath Balcony 1 projected horizontally far out, such that the spill plume rose as a free plume and did not curl inwards towards the balconies. There was no smoke contamination in Balconies 1 to 3 for this type of plume behaviour, as shown in Figure 4-1.

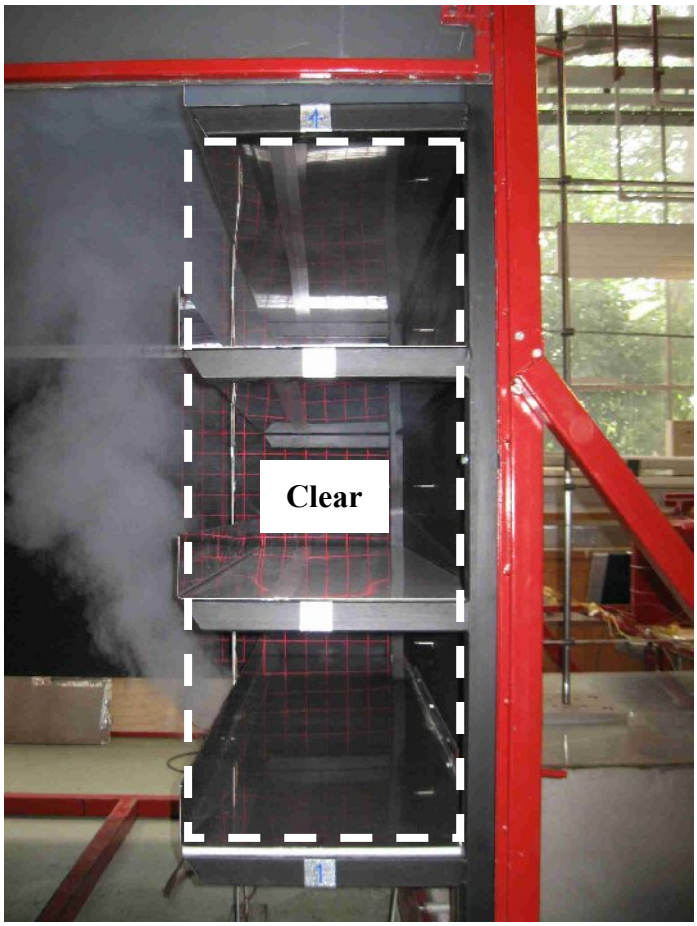

Figure 4-1: Experiment 7 – Free plume

4.1.2 'Re-attached' Plume

Generally for experiments with intermediate balcony breadths and plume widths, the horizontal projection of the balcony spill plume would not be far enough. The spill plume would then behave as a 're-attached' plume. This was when the spill plume curled inwards towards one of the upper balconies, resulting in smoke contamination on that particular balcony and subsequent balconies above (Figure 4-2). The extent of smoke contamination on the balconies (i.e. the locations and depths of smoke layers) depended on the experiment setup.

Figure 4-2: Experiment 22 – Plume re-attachment at Balcony 2

4.1.3 'Adhered' Plume

Generally for experiments with narrow balconies and wide plume widths, the balcony spill plume would have little or no horizontal projection. The balcony spill plume would 'rotate' about the edge and 'adhere' to the upstand of Balcony 1, and subsequently 'spill' into Balcony 1 (Figure 4-3). There was smoke contamination in all balconies. It is recognised that the term 'adhered plume' is conventionally used in cases where a balcony is absent and the spill plume adheres to a vertical surface above the compartment opening. However, in this research report, the 'adhered' plume is different and will refer to the spill plume 'adhering' to the upstand as described earlier.

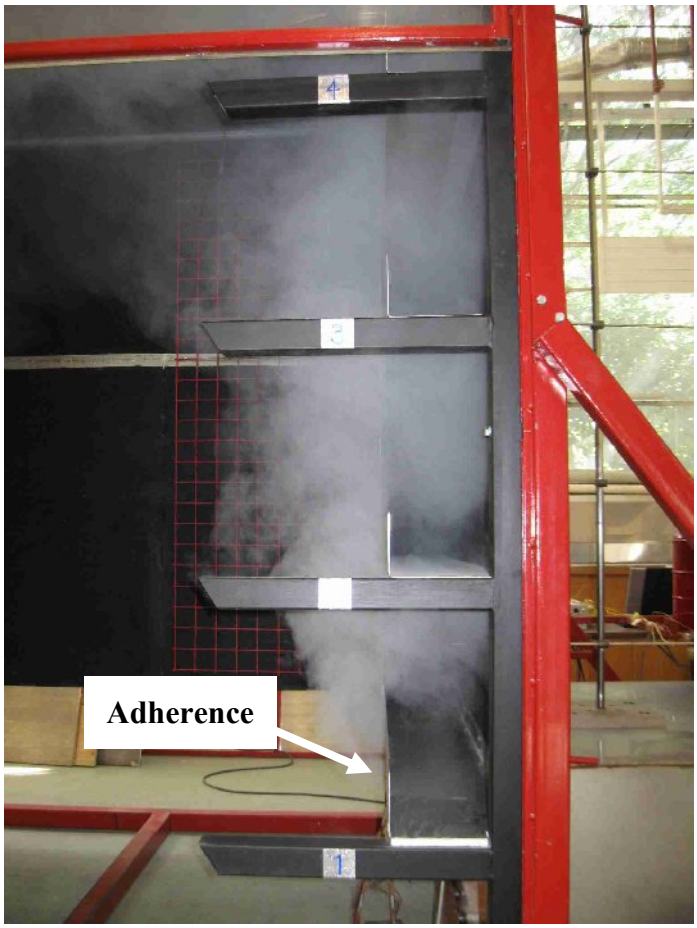

Figure 4-3: Experiment 31 – 'Adhered' plume

4.1.4 'Secondary' Balcony Spill Plume

In the event that there was smoke contamination in a balcony, the phenomenon of a 'secondary' balcony spill plume would manifest. This 'secondary' spill plume was the result of the smoke layer from a lower balcony re-entering the atrium space and 'spilling' back into the balcony above, as depicted in Figure 4-4. There would be an accumulative effect of smoke contamination in upper balconies, resulting in deeper smoke layers. The same observation was made by Hansell *et al* (1993) in their smoke flow experiments.

During some experiments, there were 'secondary' balcony spill plumes occurring at the open ends of the balconies (where the Perspex side wall was located), as depicted by the arrows in Figure 4-5. This was not desirable as these spill plumes would affect the extent of smoke contamination in upper balconies. This was a limitation of the scale model. Due to space constraints, the balconies were constructed to a width of 2 m. Wider balconies would have prevented the occurrence of 'secondary' balcony spill plumes at the open ends of the

balconies. However, at this point in time, it is not known what would be an appropriate width for the balconies.

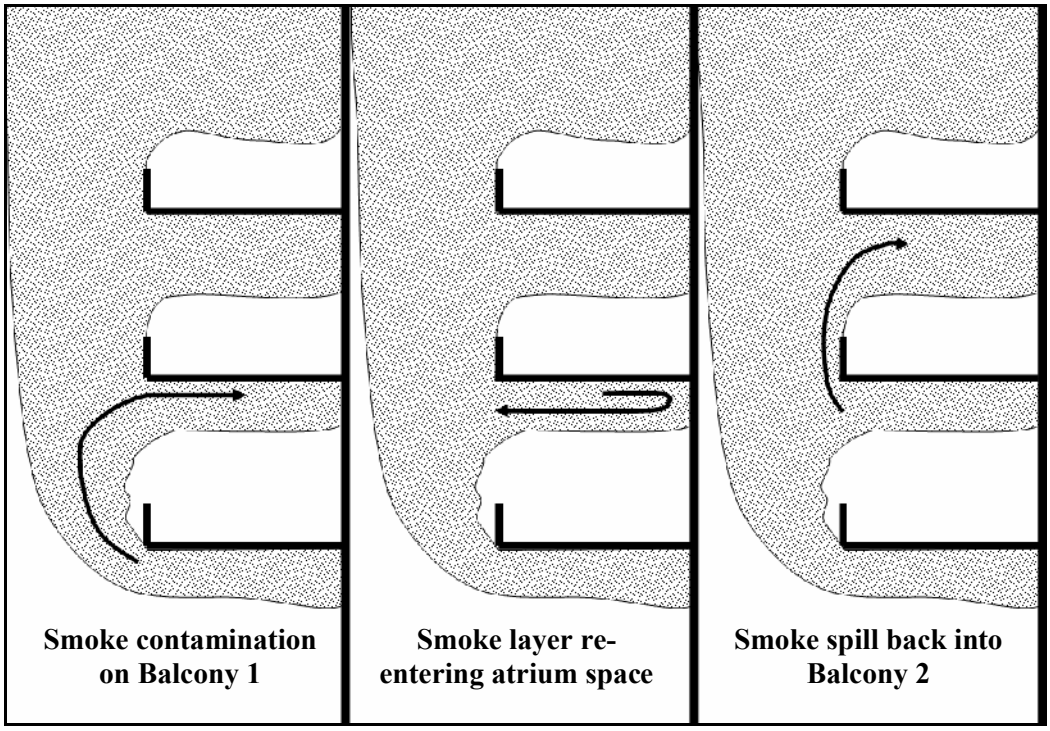

Figure 4-4: Phenomenon of a 'secondary' balcony spill plume

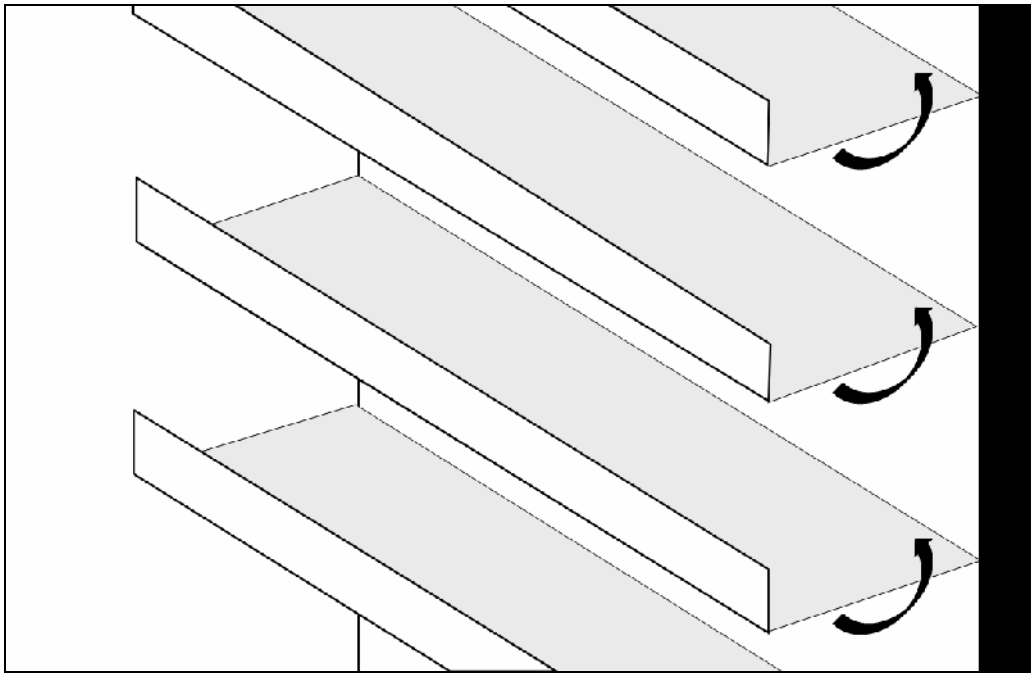

Figure 4-5: 'Secondary' balcony spill plumes occurring at open ends of balconies

4.2 Classification of Visual Observations

For a common understanding of the experiment results for visual observations, the various extents of smoke contamination in the balconies are broadly classified as follows:

(i) Clear (Figure 4-6) ⇒ No smoke was visually observed between balconies. Smoke contamination did not occur.

(ii) Shallow smoke layer (Figure 4-7) ⇒ Smoke contamination occurred. A smoke layer was visually observed in upper half of balcony height (floor to ceiling).

(iii) Deep smoke layer (Figure 4-8) ⇒ Smoke contamination occurred. A smoke layer was visually observed in lower half of balcony height (floor to ceiling).

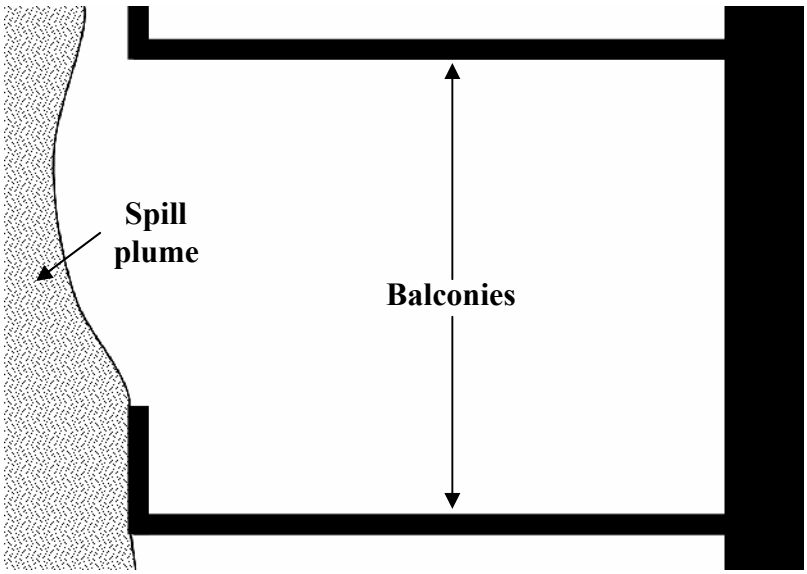

Figure 4-6: Clear – no smoke observed visually between balconies

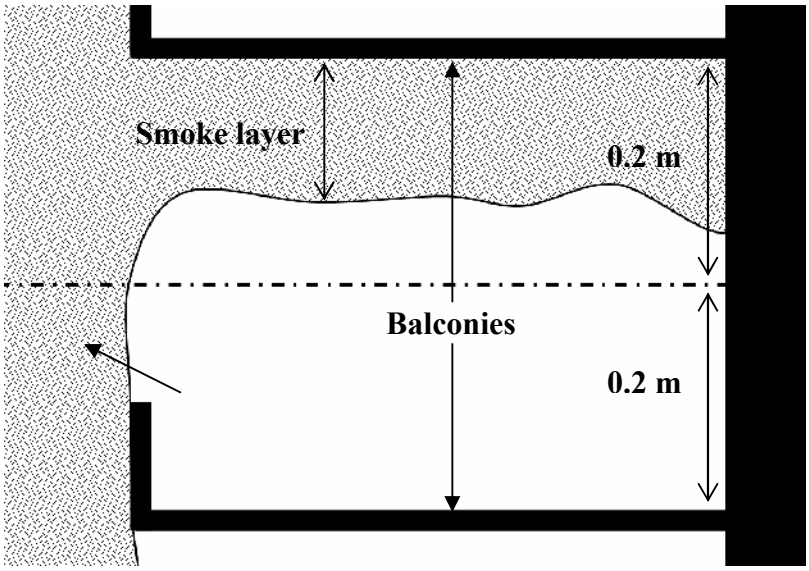

Figure 4-7: Shallow smoke layer – smoke layer visually observed in upper half of balcony height

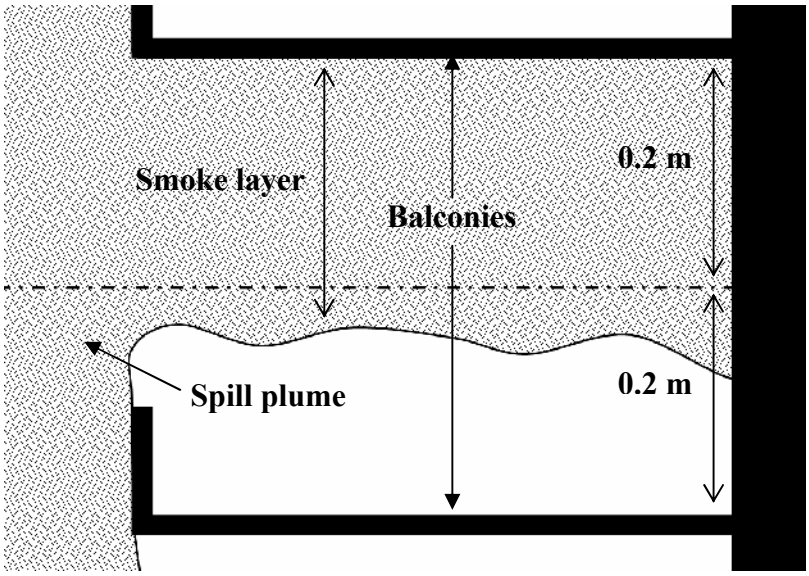

Figure 4-8: Deep smoke layer – smoke layer visually observed in lower half of balcony height

Visual observations described qualitatively can be subjective. This is especially so as the smoke layer was not always stable. As much as possible, the visual observations were carried out in a consistent manner. A summary of the visual observations is tabulated in Table 4-1. It is to note that some experiments were not conducted, as the results could be inferred from other experiments. For example, the results from Experiment 9 were inferred from Experiment 8. Given that there was no smoke contamination in the balconies for Experiment 8, there should not be any smoke contamination in the balconies for a higher fire

heat release rate in Experiment 9 due to greater momentum in the balcony spill plume. The photographic records for the visual observations are provided in Appendix B.

From Table 4-1, a pattern is clearly manifested by the different symbols and shades used to represent the various classifications of visual observations. Broadly, the extent of smoke contamination is shown to increase with decreasing balcony breadths, increasing plume widths and decreasing fire sizes. A discussion on the effects of these experiment variables is provided in Section 5.2

Table 4-1: Summary of visual observations

Experiment	Balcony Breadth , b (m)	Plume Width , w (m)	Heat Release Rate, Q_T (kW)	Balcony 1	Balcony 2	Balcony 3
1	0.50	1.0	5	✓	✓✓	✓✓
2			10	✓	✓✓	✓✓
3			15	✓	✓✓	✓✓
4		0.8	5	×	✓	✓✓
5			10	×	✓	✓✓
6			15	×	×	✓✓
7		0.6	5	×	×	×
8			10	×	×	×
9			15	(×)	(×)	(×)
10		0.4	5	×	×	×
11			10	(×)	(×)	(×)
12			15	(×)	(×)	(×)
13		0.2	5	×	×	×
14			10	(×)	(×)	(×)
15			15	(×)	(×)	(×)
16	0.30	1.0	5	✓	✓✓	✓✓
17			10	✓	✓✓	✓✓
18			15	✓	✓✓	✓✓
19		0.8	5	✓	✓	✓✓
20			10	✓	✓✓	✓✓
21			15	×	✓	✓✓
22		0.6	5	×	✓	✓✓
23			10	×	✓	✓✓
24			15	×	×	×
25		0.4	5	×	×	✓
26			10	×	×	✓
27			15	×	×	×
28		0.2	5	×	×	×
29			10	(×)	(×)	(×)
30			15	(×)	(×)	(×)
31	0.20	1.0	5	✓✓	✓✓	✓✓
32			10	✓	✓✓	✓✓
33			15	✓✓	✓✓	✓✓
34		0.8	5	✓✓	✓✓	✓✓
35			10	✓	✓✓	✓✓
36			15	✓	✓✓	✓✓
37		0.6	5	×	✓	✓✓
38			10	✓	✓	✓✓
39			15	×	✓	✓✓
40		0.4	5	×	×	✓
41			10	×	×	×
42			15	(×)	(×)	(×)
43		0.2	5	×	×	×
44			10	(×)	(×)	(×)
45			15	(×)	(×)	(×)
46	0.15	1.0	5	✓✓	✓✓	✓✓
47			10	✓✓	✓✓	✓✓
48			15	✓✓	✓✓	✓✓
49		0.8	5	✓✓	✓✓	✓✓
50			10	✓✓	✓✓	✓✓
51			15	✓	✓✓	✓✓
52		0.6	5	✓	✓✓	✓✓
53			10	✓	✓	✓✓
54			15	×	✓	✓✓
55		0.4	5	×	×	✓✓
56			10	×	×	✓
57			15	×	×	✓
58		0.2	5	×	×	✓
59			10	×	×	✓
60			15	×	×	✓

✓✓ : Deep smoke layer ✓ : Shallow smoke layer × : Clear (×) : Clear - Inferred

4.3 Temperature Readings and Profiles

4.3.1 Thermocouple Column B

The temperature readings from Thermocouple Column B were averaged over the period of 60 s for each experiment. The distances of the thermocouples above the edge of Balcony 1 were plotted against the averaged temperatures above ambient. This provided a temperature profile across the balcony edges in the vertical axis. As an example, the temperature profile for Experiment 1 with error bars of one standard deviation is shown in Figure 4-9.

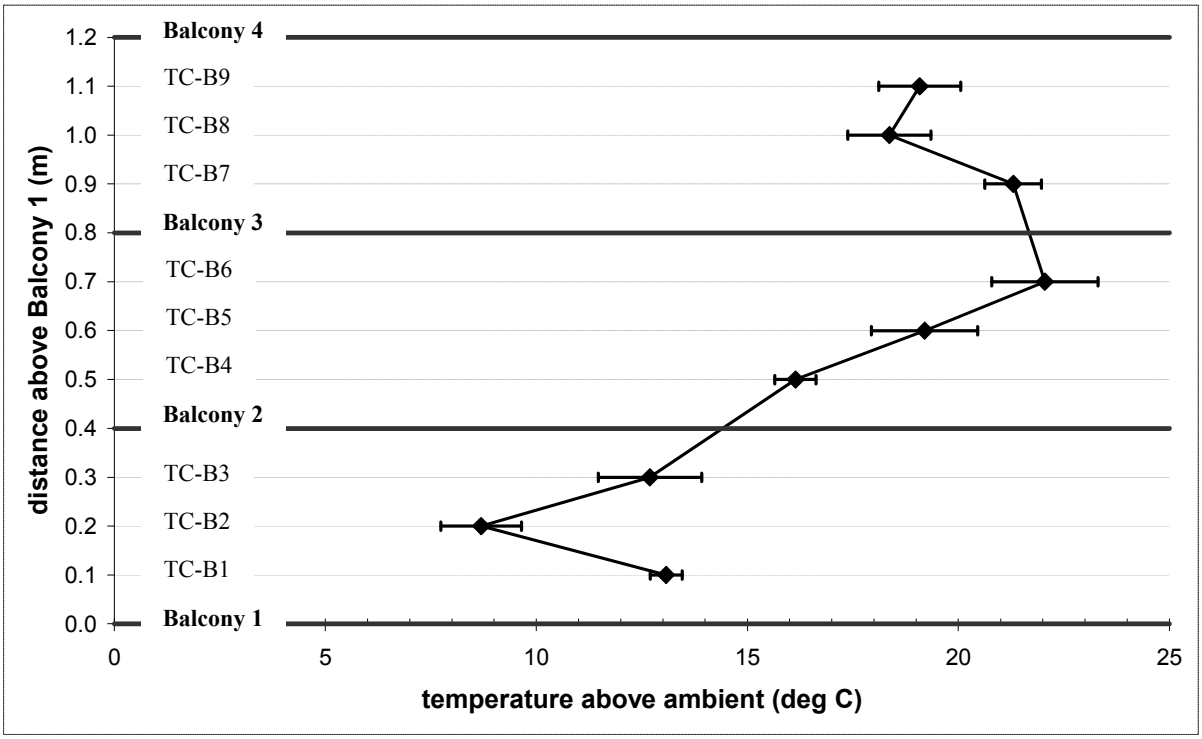

Figure 4-9: Temperature profile across balcony edge for Experiment 1

The temperature profiles across the balcony edge for the experiments are provided in Appendix C. A discussion to relate the temperature readings to the visual observations is covered in Section 5.1.

4.3.2 Thermocouple Column C

The temperature readings from Thermocouple Column C were averaged over the period of 60 s for each experiment. The averaged temperatures above ambient were plotted against the distances of the thermocouples from the atrium wall (that the balconies were attached to). The

temperature readings would include the respective thermocouple from Thermocouple Column C for each balcony at the measuring points and the respective thermocouple from Thermocouple Column B that was at mid-height of each balcony (i.e. Thermocouples B2, B5 and B8). This provided a temperature profile along the balcony breadth in the horizontal axis (at the height of 0.2 m above each balcony floor). As an example, the temperature profile of each balcony for Experiment 1 is shown in Figure 4-10.

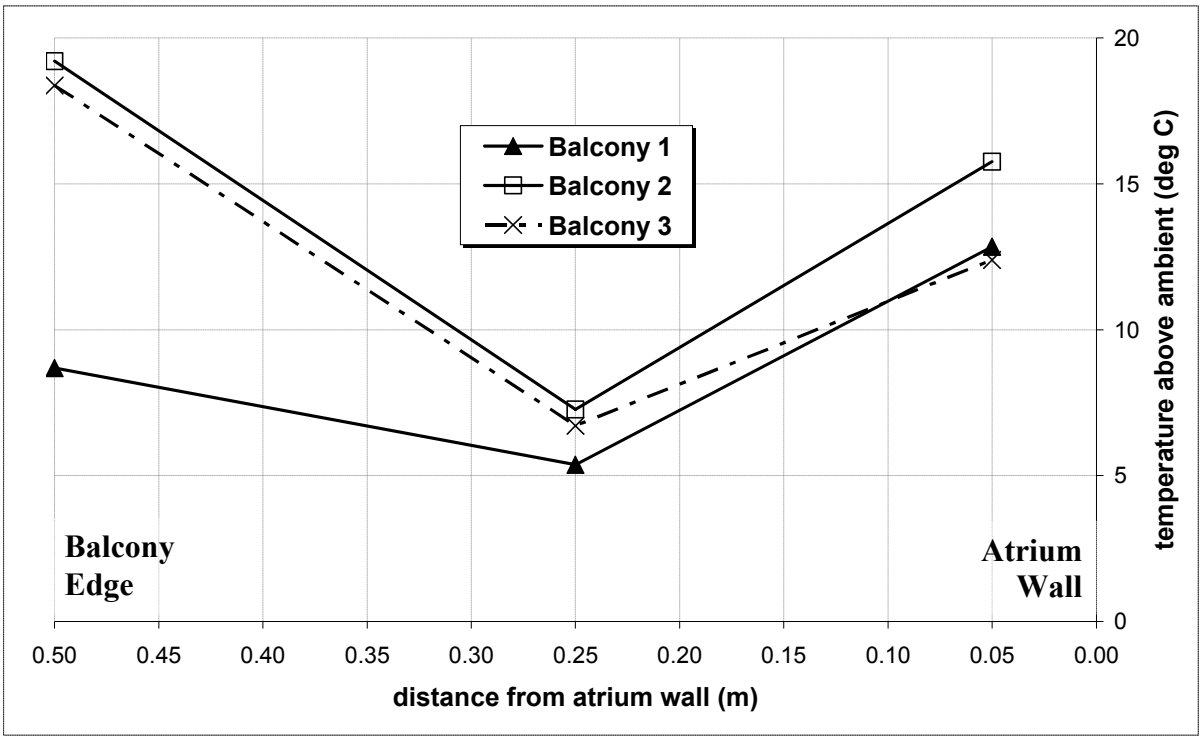

Figure 4-10: Temperature profiles along balcony breadth for Experiment 1

The temperature profiles along the balcony breadth for the experiments are provided in Appendix D. Similarly, a discussion to relate the temperature readings to the visual observations is covered in Section 5.1.

5 ANALYSIS

In meeting the objectives of this research project, the results were analysed so that guidance on the behaviour of the balcony spill plume and extent of smoke contamination in upper balconies can be developed for Fire Engineers.

5.1 Relating Temperature Readings to Visual Observations

5.1.1 Temperature Profiles across Balcony Edge

From the temperature profiles across the balcony edge, it was found that where the smoke temperatures were significantly above the ambient temperature, smoke was visually observed in the balconies (refer to Appendix C). To establish this relationship clearly, a simple method of a temperature marker of 10 °C above ambient temperature was used to relate the temperature readings to the visual observations. That is, where the temperature reading was less than 10 °C above ambient temperature, smoke was not expected to be visually observed; where the temperature reading was more than 10 °C above ambient temperature, smoke was expected to be visually observed. The temperature marker of 10 °C above ambient temperature was used for all four balcony breadths as it best-fitted the visual observations for the experiments.

Using Experiment 1 as an illustration (Figure 5-1), smoke was expected to be visually observed at the level of Thermocouple B3 in Balcony 1 (i.e. a shallow smoke layer was expected). A deep smoke layer was expected to be visually observed in Balconies 2 and 3. This was consistent with the visual observations for Experiment 1 as shown in Table 5-1. In this analysis, the temperature reading of Thermocouple B1 was ignored, as it tend to record higher temperatures due to the initial ‘adherence’ of the balcony spill plume to the upstand of Balcony 1.

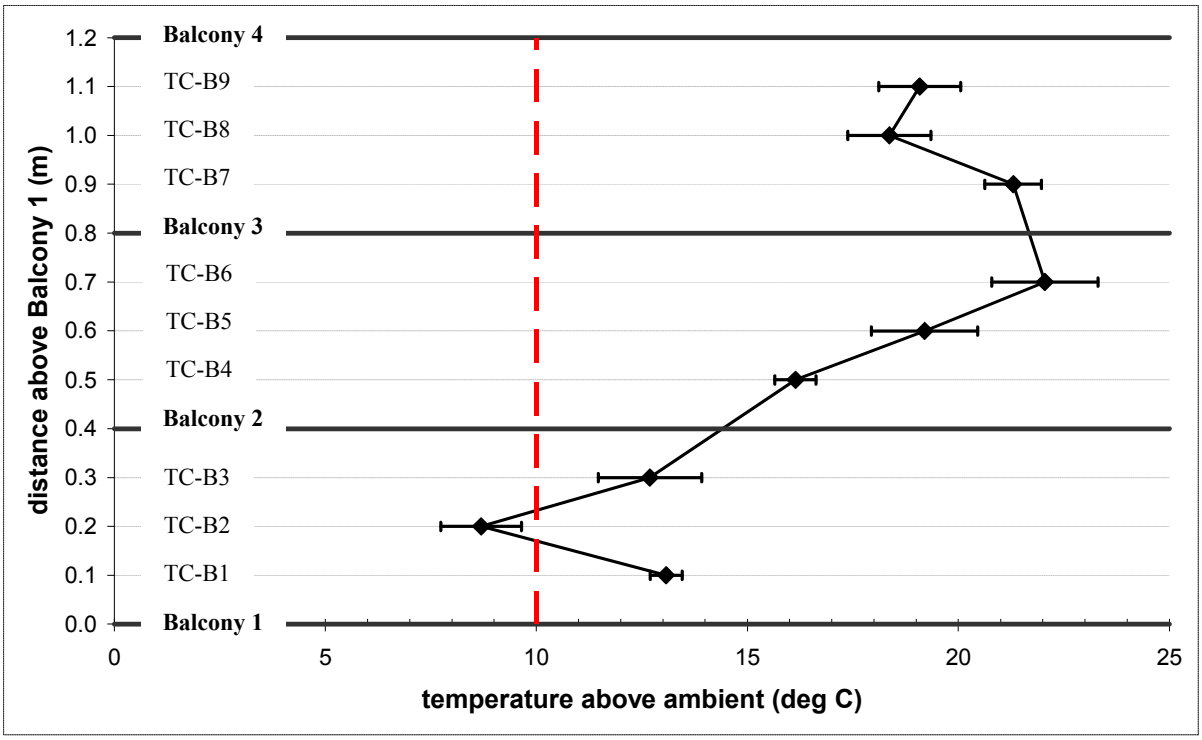

Figure 5-1: Temperature profile across balcony edges for Experiment 1 (with marker)

Table 5-1: Visual observations for Experiment 1

Experiment	Balcony Breadth , b (m)	Plume Width, w (m)	Heat Release Rate , Q_T (kW)	Balcony 1	Balcony 2	Balcony 3
1	0.5	1.0	5	✓	✓✓	✓✓

✓✓: Deep smoke layer ✓: Shallow smoke layer

From this interesting relationship, further analysis was conducted to relate the effect of the experiment variables to the extent of smoke contamination in upper balconies (refer to Section 5.2).

5.1.2 Temperature Profiles along Balcony Breadth

The same method of a temperature marker was used to relate the temperature readings to the visual observations (refer to Appendix D). In this case, where the temperature reading was less than the temperature marker, the smoke layer was not expected to fall below 0.2 m (i.e. a shallow smoke layer expected); where the temperature reading was more than the temperature marker, the smoke layer was expected to fall below 0.2 m (i.e. a deep smoke layer expected).

Using Figure 5-2 and Figure 5-3 for Experiment 1 as illustrations, the smoke layer was not expected to fall below 0.2 m on Balcony 1 except near the atrium wall (i.e. a shallow smoke layer expected). The temperatures near the atrium wall tend to be higher due to local deepening of the smoke layer, as shown in Figure 5-3. The smoke layers were expected to fall below 0.2 m on most parts of Balconies 2 and 3 (i.e. deep smoke layers expected). Again, this was consistent with the visual observations for Experiment 1 (Table 5-1). The same temperature marker of 10 °C above ambient temperature was used for all four balcony breadths as it best-fitted the visual observations for the experiments. However, for any further analysis to be relevant, it would have to delve into tenability within the balconies. As the scope of this research project did not include tenability within the balconies, no further analysis was conducted.

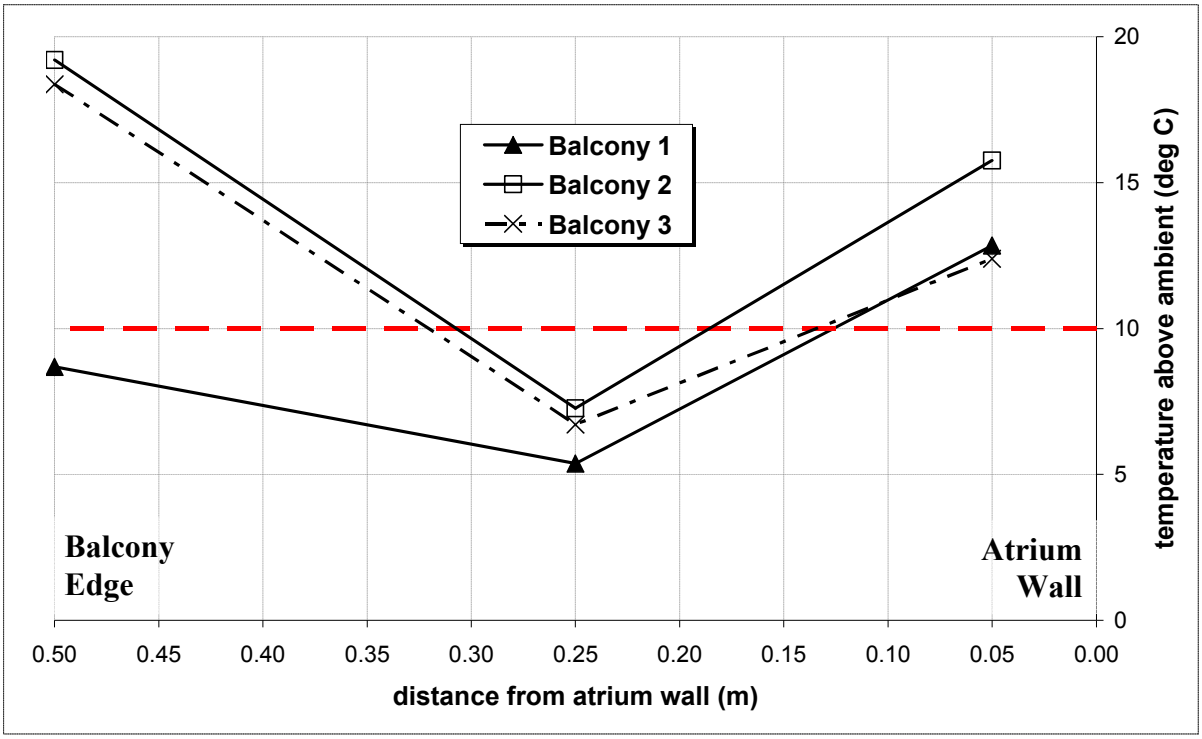

Figure 5-2: Temperature profiles along balcony breath for Experiment 1 (with marker)

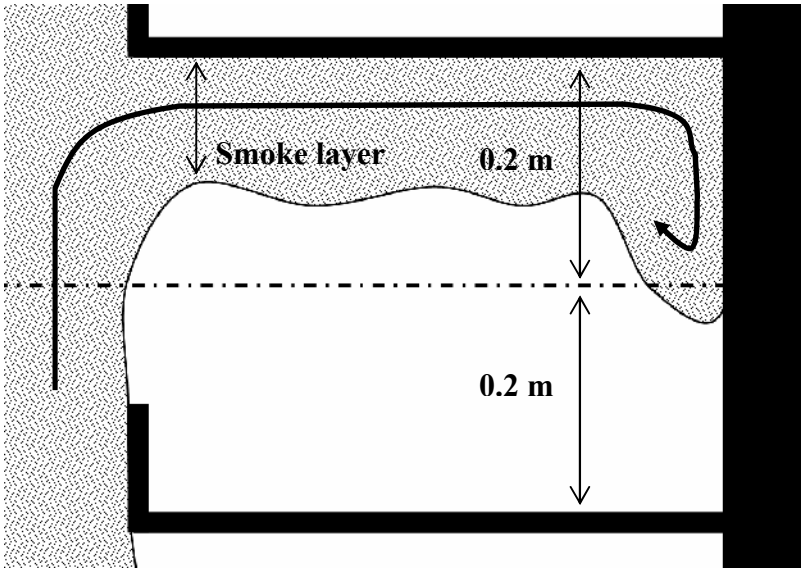

Figure 5-3: Local deepening of the smoke layer near the atrium wall

5.2 Effects of Experiment Variables on Smoke Contamination

In this section, the effects of the three experiment variables are discussed with reference to the visual observations in Table 4-1.

5.2.1 Balcony Breadth

The extent of smoke contamination in upper balconies increased as the balcony breadth decreased. This finding is consistent with the findings by Hansell *et al* (1993), where it was found that balcony breadths more than 2 m would allow the spill plume to rise through the atrium as a free plume, while balcony breadths less than 2 m would cause smoke-logging (i.e. smoke contamination) between the spill plume and the atrium wall. One possible reason is the Coanda effect, as explained in Section 1.2.

5.2.2 Plume Width

For all four balcony breadths, the extent of smoke contamination in the balconies increased as the plume width increased. One possible reason for this finding lies with the aspect ratio of the smoke layer (of the balcony spill plume) flowing beneath Balcony 1. For a given fire heat release rate, the aspect ratio of the smoke layer would change such that the depth of the smoke layer decreased as the plume width increased.

As with the findings by Yokoi (1960), the balcony spill plume would project horizontally further for a narrow width and deep smoke layer, in comparison to a wide width and shallow smoke layer. For the latter, the spill plume would curl inwards towards the balconies.

5.2.3 Fire Size

Generally, for experiments with the same geometrical variables (i.e. balcony breadth and plume width), the differences in the extent of smoke contamination were not significant for the fire sizes with heat release rates of 5 kW, 10 kW and 15 kW. For the few cases where the differences were noticeably significant, the extent of smoke contamination was more severe for a lower fire heat release rate as compared to a higher fire heat release rate (e.g. Experiments 34 to 36 and Experiments 52 to 54). This is expected given that a higher fire heat release rate would lead to an increase in the momentum of the fire gases and in turn, a further horizontal projection of the balcony spill plume. The findings are consistent with that found by Hansell *et al* (1993).

5.3 Aspect Ratio of Plume Width to Balcony Breadth

Since the effect of fire size was relatively less significant compared to those of balcony breadth and plume width, an analysis involving the aspect ratio of plume width to balcony breadth was performed. The purpose of this analysis is to determine whether this aspect ratio can be used to provide generic guidance to Fire Engineers in atrium design. The aspect ratios for the experiments are highlighted in Table 5-2, where it is shown that the extent of smoke contamination increased as the aspect ratio increased.

Table 5-2: Aspect ratio of plume width to balcony breadth

Experiment	Balcony Breadth, *b* (m)	Plume Width, *w* (m)	Aspect Ratio, *w/b*	Balcony 1	Balcony 2	Balcony 3
1	0.50	1.0	**2.0**	✓	✓✓	✓✓
2				✓	✓✓	✓✓
3				✓	✓✓	✓✓
4		0.8	**1.6**	×	✓	✓✓
5				×	✓	✓✓
6				×	×	✓✓
7		0.6	**1.2**	×	×	×
8				×	×	×
9				(×)	(×)	(×)
10		0.4	**0.8**	×	×	×
11				(×)	(×)	(×)
12				(×)	(×)	(×)
13		0.2	**0.4**	×	×	×
14				(×)	(×)	(×)
15				(×)	(×)	(×)
16	0.30	1.0	**3.3**	✓	✓✓	✓✓
17				✓	✓✓	✓✓
18				✓	✓✓	✓✓
19		0.8	**2.7**	✓	✓	✓✓
20				✓	✓✓	✓✓
21				×	✓	✓✓
22		0.6	**2.0**	×	✓	✓✓
23				×	✓	✓✓
24				×	×	×
25		0.4	**1.3**	×	×	✓
26				×	×	✓
27				×	×	×
28		0.2	**0.7**	×	×	×
29				(×)	(×)	(×)
30				(×)	(×)	(×)
31	0.20	1.0	**5.0**	✓✓	✓✓	✓✓
32				✓	✓✓	✓✓
33				✓✓	✓✓	✓✓
34		0.8	**4.0**	✓✓	✓✓	✓✓
35				✓	✓✓	✓✓
36				✓	✓✓	✓✓
37		0.6	**3.0**	×	✓	✓✓
38				✓	✓	✓✓
39				×	✓	✓✓
40		0.4	**2.0**	×	×	✓
41				×	×	×
42				(×)	(×)	(×)
43		0.2	**1.0**	×	×	×
44				(×)	(×)	(×)
45				(×)	(×)	(×)
46	0.15	1.0	**6.7**	✓✓	✓✓	✓✓
47				✓✓	✓✓	✓✓
48				✓✓	✓✓	✓✓
49		0.8	**5.3**	✓✓	✓✓	✓✓
50				✓✓	✓✓	✓✓
51				✓	✓✓	✓✓
52		0.6	**4.0**	✓	✓✓	✓✓
53				✓	✓	✓✓
54				×	✓	✓✓
55		0.4	**2.7**	×	×	✓✓
56				×	×	✓
57				×	×	✓
58		0.2	**1.3**	×	×	✓
59				×	×	✓
60				×	×	✓

✓✓ : Deep smoke layer ✓ : Shallow smoke layer × : Clear (×) : Clear - Inferred

By plotting the aspect ratio to the number of balconies with smoke contamination (Figure 5-4), it is shown that there was no smoke contamination in Balconies 1 to 3 where the aspect ratio ≤ 1, while there was smoke contamination in more than one upper balcony where the aspect ratio ≥ 3.

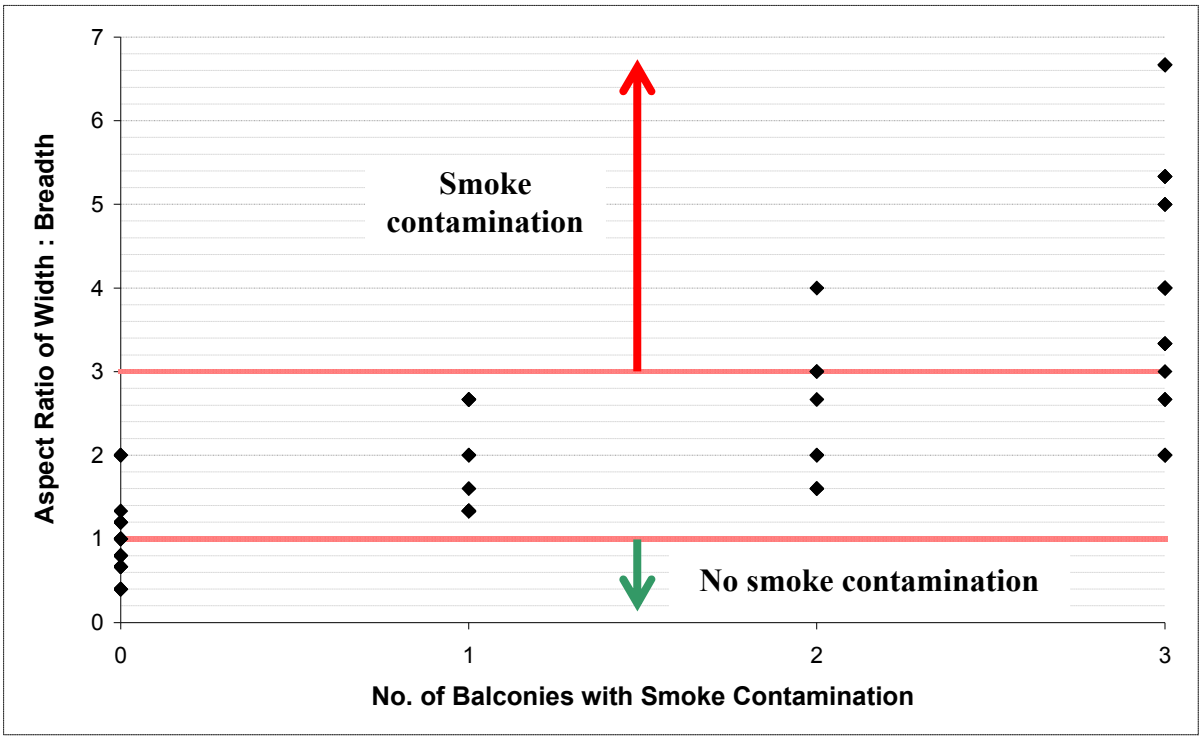

Figure 5-4: Plot of aspect ratio of plume width to balcony breadth against number of balconies with smoke contamination

5.4 Non-dimensional Correlation

For 1 < aspect ratio < 3, smoke contamination may or may not occur in the balconies. There is a need to provide further guidance to establish the extent of smoke contamination in the balconies. An analysis involving non-dimensional correlation of related experiment variables was performed. The key benefit of using non-dimensional analysis was that the resulting correlation would be applicable to a specified range of values, rather than to discrete values.

To perform the non-dimensional analysis for this research project, two new variables were introduced, namely the height of smoke contamination above Balcony 1 (i.e. the height above Balcony 1 at which the balcony spill plume curls inwards and crosses the vertical axis of the

balcony edge) and the depth of smoke layer (of the balcony spill plume) flowing beneath Balcony 1.

5.4.1 Height of Smoke Contamination

The height of smoke contamination above Balcony 1, H is obtained by locating the intersection point between the temperature profile across the balcony edge and the temperature marker (as described in Section 5.1). Using the temperature profile of Experiment 1 as an illustration (Figure 5-5), H is found to be 0.24 m.

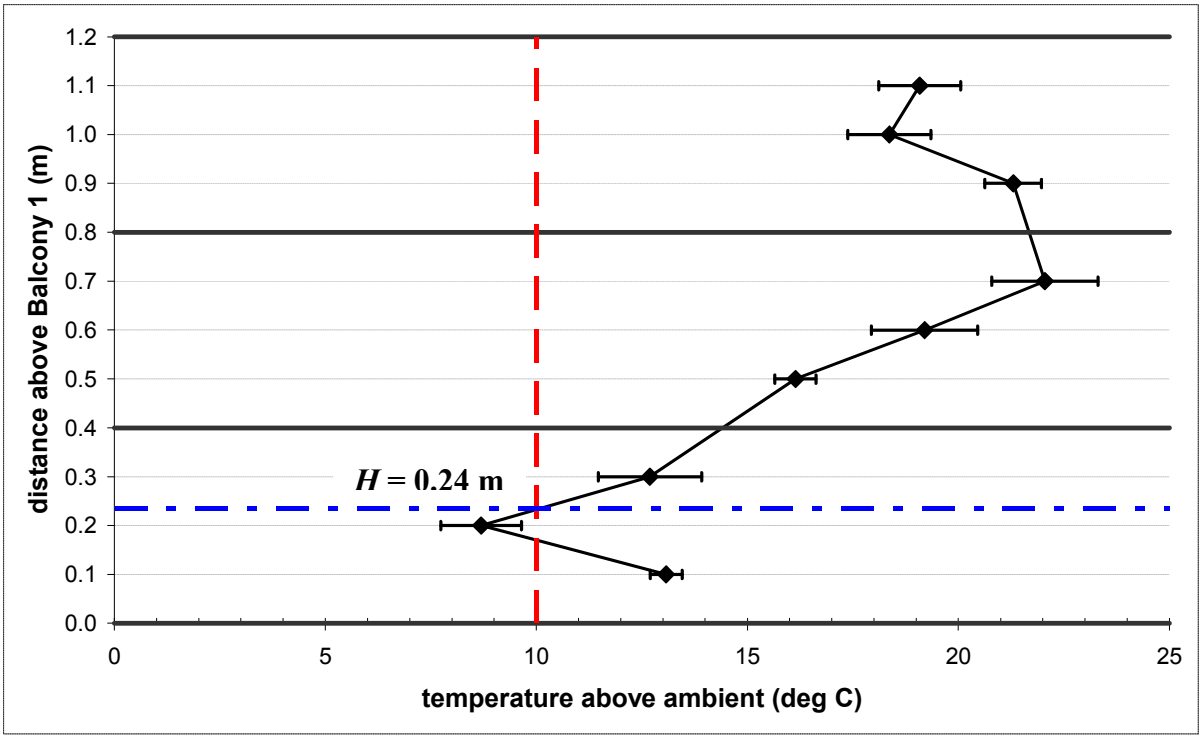

Figure 5-5: ***H*** **value for Experiment 1**

If the method of a temperature marker was not suitable (for example, there was no point of intersection for Experiment 6), H was approximated from the visual observations. Using Experiment 6 as an example, H was approximated as 0.9 m. The values for H for the experiments are shown in Table 5-3.

Table 5-3: Values for *H* for the experiments

Experiment	Height of Smoke Contamination, *H* (m)
1	0.24
2	0.25
3	0.25
4	0.62
5	0.63
6	(0.90)
7	–
8	–
9	–
10	–
11	–
12	–
13	–
14	–
15	–
16	0.28
17	0.22
18	(0.30)
19	(0.25)
20	(0.25)
21	(0.70)
22	0.65
23	0.70
24	(1.10)
25	(1.10)
26	(1.10)
27	–
28	–
29	–
30	–
31	(0.10)
32	(0.15)
33	(0.15)
34	(0.15)
35	(0.20)
36	0.28
37	0.65
38	(0.25)
39	(0.70)
40	(1.10)
41	–
42	–
43	–
44	–
45	–
46	(0.10)
47	(0.10)
48	(0.10)
49	(0.15)
50	(0.15)
51	0.21
52	0.26
53	(0.30)
54	(0.60)
55	(0.90)
56	(1.00)
57	(1.10)
58	(1.00)
59	(1.10)
60	(1.10)

(XXX) : approximated value – : no smoke contamination

5.4.2 Depth of Smoke Layer

As mentioned in Section 2.4, the depth of smoke layer, *d* of the balcony spill plume flowing beneath Balcony 1 is dependent on the fire heat release rate. In the analysis using aspect ratio of plume width to balcony breadth, the effect of fire size on the extent of smoke contamination, being less significant, was ignored. On the other hand, the use of the depth of smoke layer, *d* in this non-dimensional correlation analysis would include the dependence on fire size. However, the depth of smoke layer, *d* was not measured in the experiments. Since the plume widths and fire sizes were the same as Harrison's (2009), the values were referenced as:

Table 5-4: Referenced values for depth of smoke layer, *d*

Plume Width, *w* (m)	Heat Release Rate, Q_T (kW)	Depth, *d* (m)
1.0	5	0.100
	10	0.115
	15	0.125
0.8	5	0.105
	10	0.115
	15	0.135
0.6	5	0.110
	10	0.120
	15	0.140
0.4	5	0.115
	10	0.125
	15	0.145
0.2	5	0.135
	10	0.155
	15	0.170

In the complementary research work by Harrison (2009), a balcony breadth of 0.3 m was used and this breadth was not varied. However, as channelling screens were utilised in this research work and the smoke layer flowing beneath Balcony 1 was well contained within the depths of the screens, it is reasonable to assume that the values for *d* were similar for all four balcony breadths.

5.4.3 Correlation Result

By suitably combining experiment variables of b, w, H and d, a number of non-dimensional terms could be created. From the non-dimensional terms, any two terms could be chosen and plotted on a graph to examine for a relationship amongst the data points. Should there be some form of relationship amongst the data points, a best-fit curve would be plotted to obtain a correlation between the chosen non-dimensional terms.

Amongst the several combinations, the non-dimensional terms $\frac{w}{d}$ and $\frac{H}{b}$ were chosen and plotted on the x-axis and y-axis respectively. In view of the findings by Yokoi (1960) as mentioned in Section 2.4, the term $\frac{w}{d}$ was found suitable to relate to the behaviour/trajectory of the balcony spill plume. Experiments without a value for H (i.e. no smoke contamination) were omitted. The data points on the resulting plot displayed a relationship, as shown in Figure 5-6.

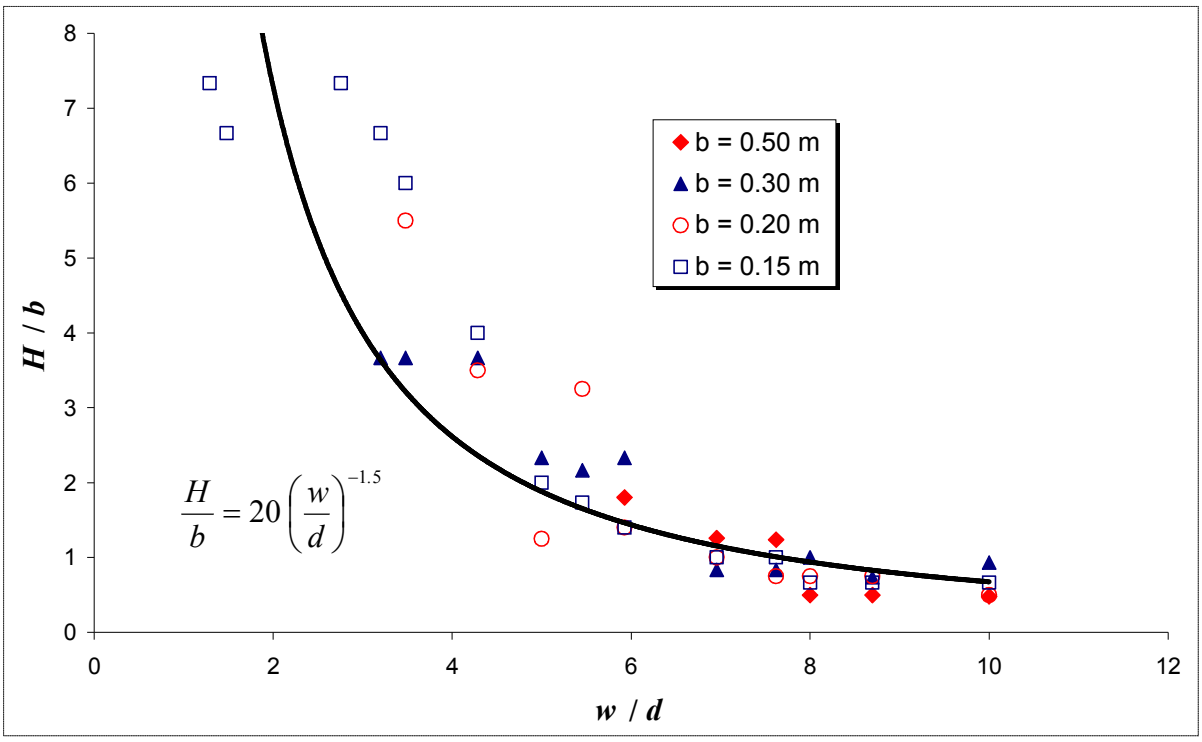

Figure 5-6: Plot for non-dimensional correlation

A best-fit correlation was obtained as follows:

$$\frac{H}{b} = 20\left(\frac{w}{d}\right)^{-1.5} \quad \Rightarrow \quad H = 20\,b \times \left(\frac{d}{w}\right)^{1.5} \tag{4}$$

The correlation resulted in an equation that could calculate the height of smoke contamination above Balcony 1, H (at which the balcony spill plume curls inwards and crosses the vertical axis of the balcony edge). The smoke layer depth, d can be obtained using the established methods from Morgan *et al* (1999) or Hansell (1993), or from any other suitable methods. As the correlation was empirically obtained, the limits applicable to the equation shall follow the range of experiment variables, as follows:

$$0.15 \le b \le 0.50 \qquad (1.5 \le b \le 5.0 \text{ at full scale}) \tag{5}$$

$$0.10 \le \frac{d}{w} \le 0.85 \tag{6}$$

However, the correlation equation should be used with caution, as the deviations from the experiment results were significant for a short balcony breadth (i.e. 0.15 m). Additionally, for atrium designs with geometries that are very different from that of the experiments, caution should also be exercised when using the correlation equation. The presence of balconies and upstands can either cause the balcony spill plume to either move further from or curl inwards towards the atrium wall. This was also noted by Hansell *et al* (1993) in one of their experiments involving two balconies. It is likely that a correction factor to the correlation equation is required for different vertical separation distances between balconies and different heights of upstands. Further research in this area is desired.

5.5 Comparison with Hansell *et al* (1993)

The only aspect ratio of plume width to balcony breadth in the experiments by Hansell *et al* (1993) was 4.2. There was re-attachment of the rising spill plume to the atrium wall. This would suggest that there would be smoke contamination in upper balconies, had there been balconies above the fire compartment. This would be in agreement with the

analysis in Section 5.3, in that smoke contamination in more than one upper balcony is likely for an aspect ratio ≥ 3.0.

It would also have been interesting to apply the correlation equation to the experiments by Hansell *et al* (1993) and compare the results with his findings. Unfortunately, this would not be relevant as the findings by Hansell *et al* (1993) were for re-attachment height of the balcony spill plume at the atrium wall, whereas H obtained from the correlation equation is the height above Balcony 1 at which the balcony spill plume curls inwards and crosses the vertical axis of the balcony edge (refer to Figure 5-7).

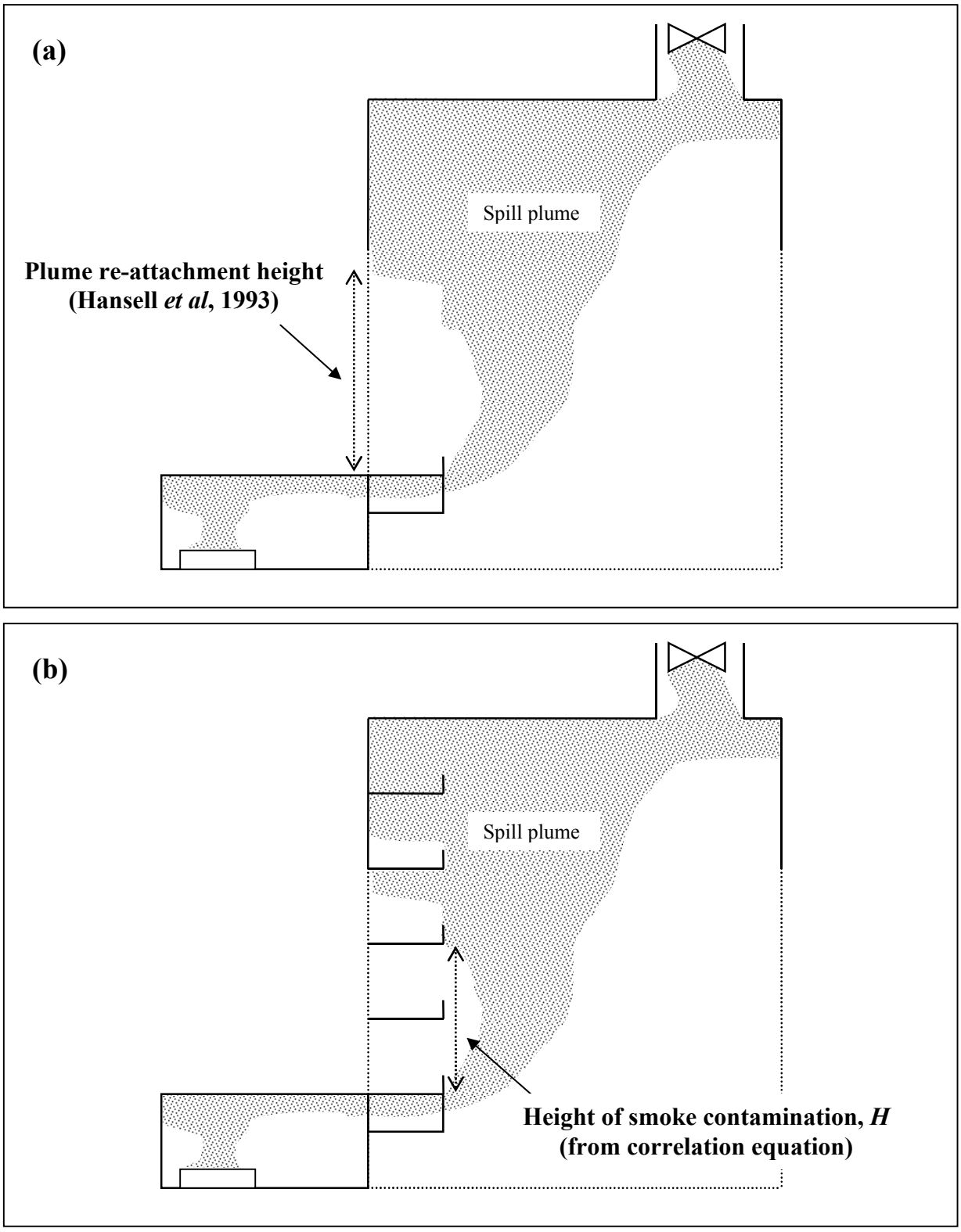

Figure 5-7: a – Plume re-attachment height (Hansell *et al*, 1993); b – Height of smoke contamination, *H* (from correlation equation)

6 CONCLUSIONS

The conclusions to this research project are as follows:

(i) The extent of smoke contamination in upper balconies increased as the balcony breadth decreased. Conversely, the extent of smoke contamination in upper balconies increased as the plume width increased.

(ii) The differences in the extent of smoke contamination were not significant for the different fire sizes. Where the differences were noticeably significant, the extent of smoke contamination was more severe for a lower fire heat release rate as compared to a higher fire heat release rate.

(iii) The aspect ratio of plume width to balcony breadth can be used to provide generic guidance in atrium design with respect to smoke contamination in upper balconies. For aspect ratio ≤ 1.0, smoke contamination in any upper balcony is unlikely; whereas for aspect ratio ≥ 3.0, smoke contamination in more than one upper balcony is likely.

(iv) For 1.0 < aspect ratio < 3.0, an empirical correlation was developed to provide further guidance on the extent of smoke contamination in upper balconies. The height of smoke contamination above Balcony 1, H (at which the balcony spill plume curls inwards and crosses the vertical axis of the balcony edge) is calculated as:

$$H = 20\, b \times \left(\frac{d}{w} \right)^{1.5}$$

(v) The correlation equation to determine H is to be used with caution. It is likely that a correction factor to the correlation equation is required for different vertical separation distances between balconies and different heights of upstands.

(vi) This research project has met the objective to systematically investigate the effects of varying balcony breadths, plume widths and fire sizes on smoke contamination in upper balconies by a balcony spill plume in an atrium. The results broadly corresponds

to that of Hansell *et al* (1993) in that the balcony breadth has an effect on the behaviour of the balcony spill plume. However, this research project provides more details and improved guidance on the effects of balcony breadth, plume width and fire size collectively.

7 FURTHER WORK

Further work is recommended in the following areas:

(i) This research project is primarily a qualitative study on the balcony spill plume. It provides qualitative results on the behaviour of the balcony spill plume and the extent of smoke contamination in upper balconies given varying balcony breadths, plume widths and fire sizes. There was no quantification of the extent of smoke contamination in the balconies. Hence, there was no measure of tenability within the balconies as a means of escape. Further research can be conducted to quantify the extent of smoke contamination and determine the tenability within the balconies.

(ii) There were some limitations to the experiment setup. Due to the need to contain and exhaust the hot smoke properly for health and safety reasons, Balconies 4 and 5 were contaminated by the smoke layer in the exhaust hood. If space is not a constraint, the smoke exhaust hood can be raised higher, so that more levels of balconies can be constructed for further investigation. Additionally, wider balconies can be constructed to prevent 'secondary' balcony spill plumes at the open ends of the balconies.

(iii) The atrium design of the scale model was kept simple as a typical fully open atrium with balconies 0.4 m vertically apart. The balcony edges were vertically aligned and the upstands were full vertical surfaces. Further research can be conducted for other atrium design parameters, such as by varying the vertical separation between balconies or the height of upstands, by having balcony edges that are not aligned or upstands that are not full vertical surfaces (e.g. balustrades).

(iv) As mentioned in Section 5.4, further research is desired to provide a better correlation to establish the extent of smoke contamination in upper balconies. The effects of the balcony and upstand positions on the balcony spill plume can be investigated more thoroughly.

(v) CFD simulations could be performed as a form of comparison to the experiment results. Where space is a constraint or parameters are too complex to be controlled

experimentally (e.g. growing fires), CFD simulations could be an alternative means to experimental work.

8 APPENDICES

The list of appendices is as follows:

(i) Appendix A – References

(ii) Appendix B – Photographic Records

(iii) Appendix C – Temperature Profiles across Balcony Edge

(iv) Appendix D – Temperature Profiles along Balcony Breadth

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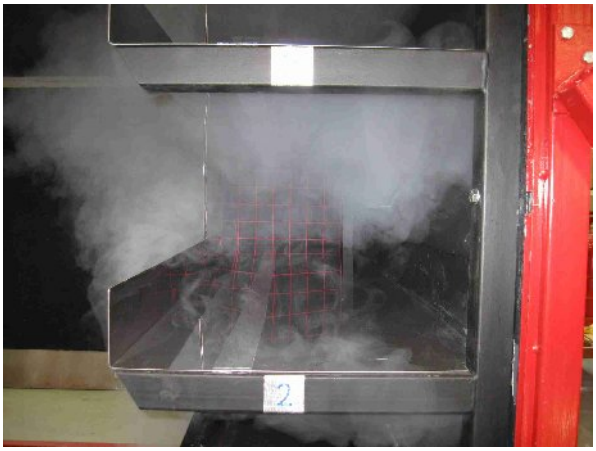
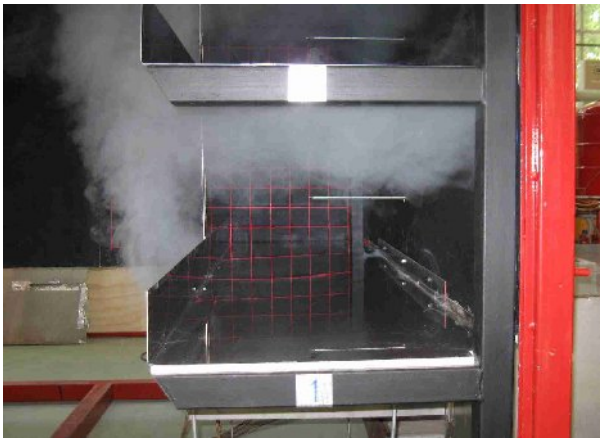
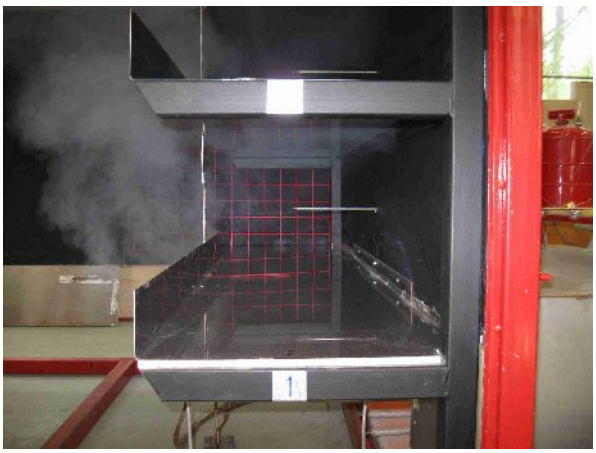
PHOTOGRAPHIC RECORDS

Experiment No. = 1
Balcony Breadth = 500 mm
Plume Width = 1000 mm
Heat Release Rate = 5 kW

Balcony Level	Photograph
3	
2	
1	

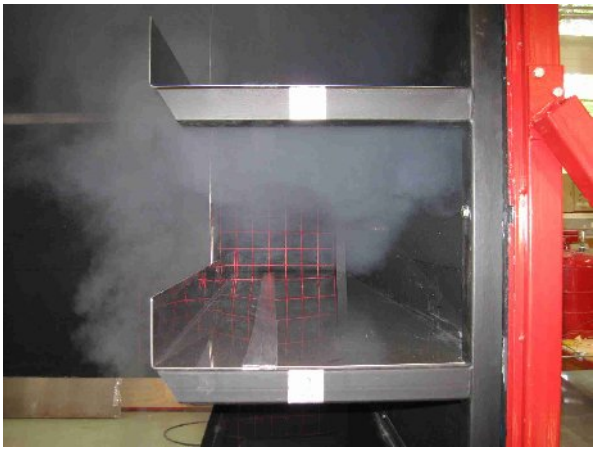
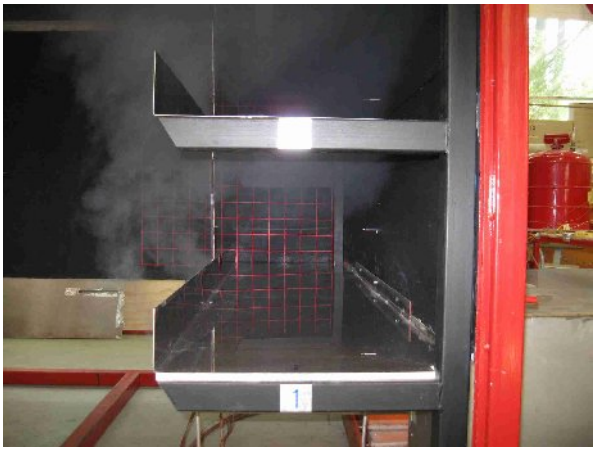
PHOTOGRAPHIC RECORDS

Experiment No. = **2**
Balcony Breadth = **500 mm**
Plume Width = **1000 mm**
Heat Release Rate = **10 kW**

Balcony Level	Photograph
3	
2	
1	

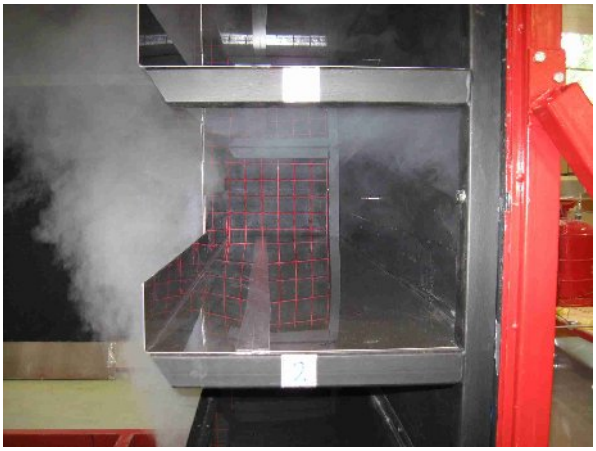
PHOTOGRAPHIC RECORDS

Experiment No. = **3**
Balcony Breadth = **500 mm**
Plume Width = **1000 mm**
Heat Release Rate = **15 kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **4**
Balcony Breadth = **500** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

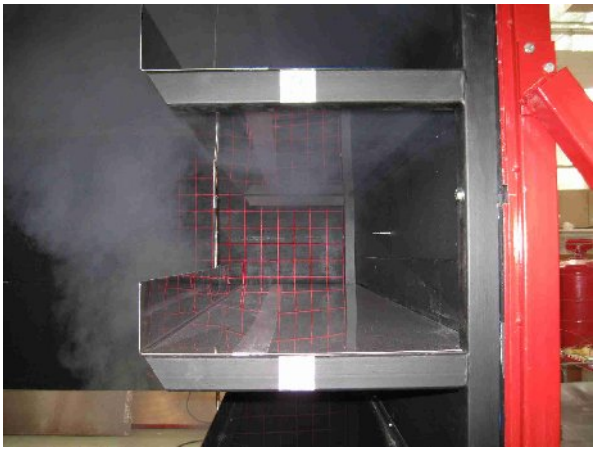
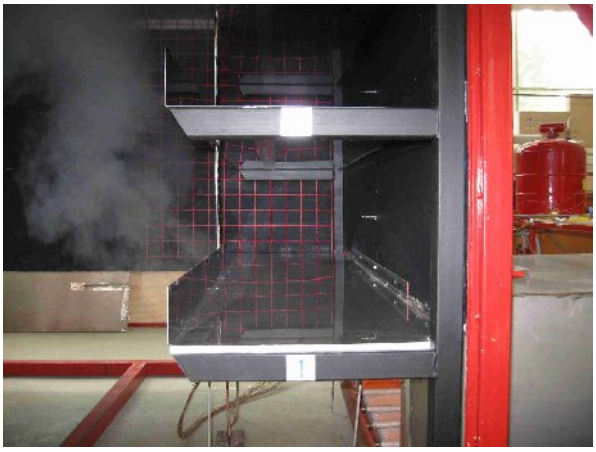
PHOTOGRAPHIC RECORDS

Experiment No. = **5**
Balcony Breadth = **500** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

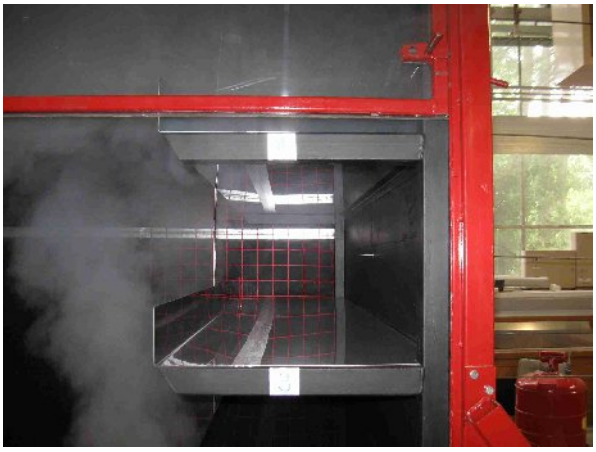
PHOTOGRAPHIC RECORDS

Experiment No. = **6**
Balcony Breadth = **500** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **7**
Balcony Breadth = **500** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
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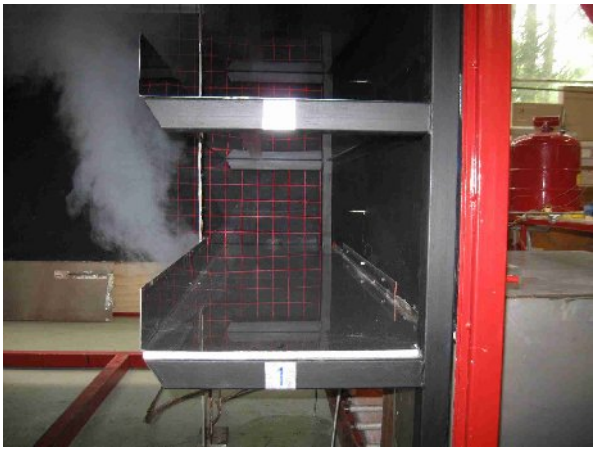
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **8**
Balcony Breadth = **500** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
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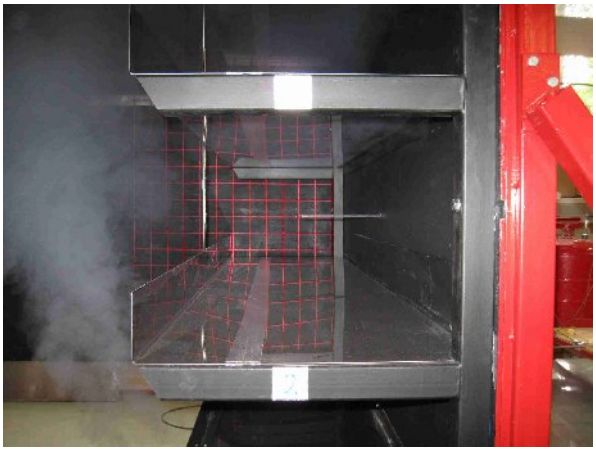
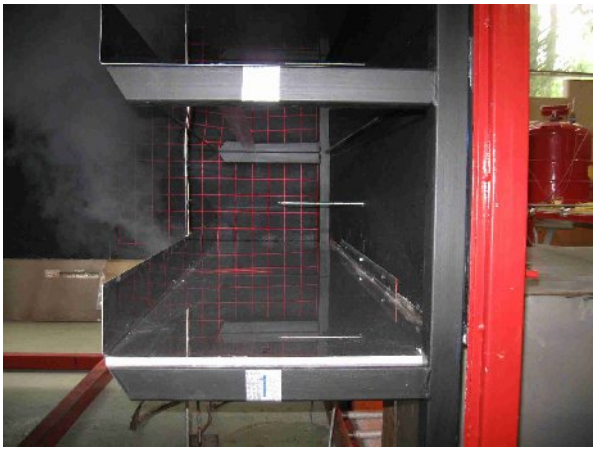
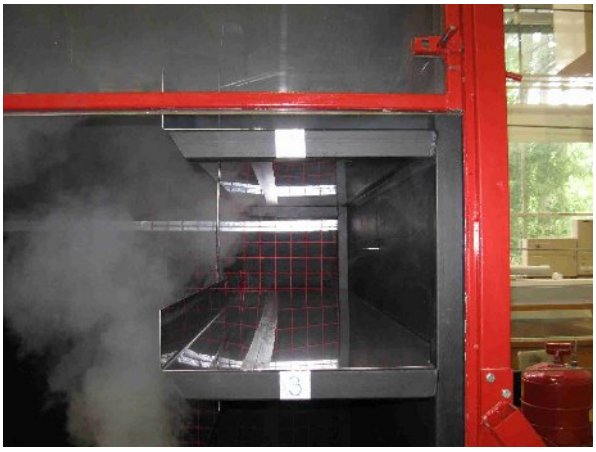
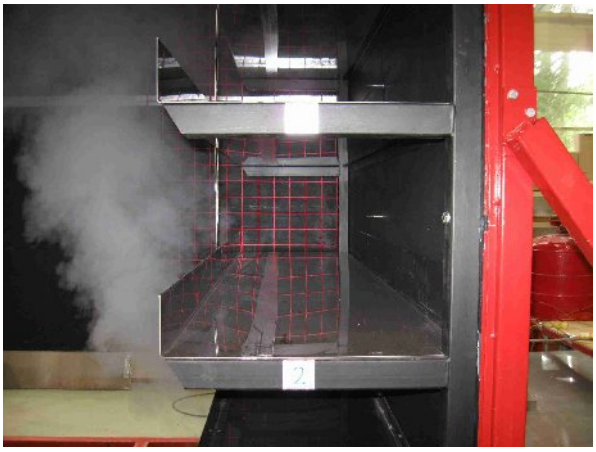
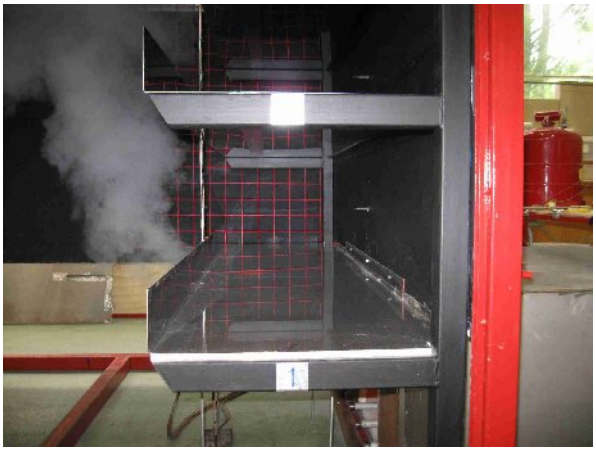
2	
1	

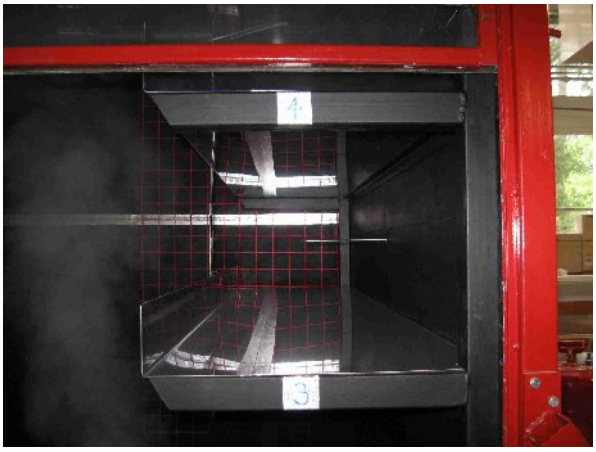
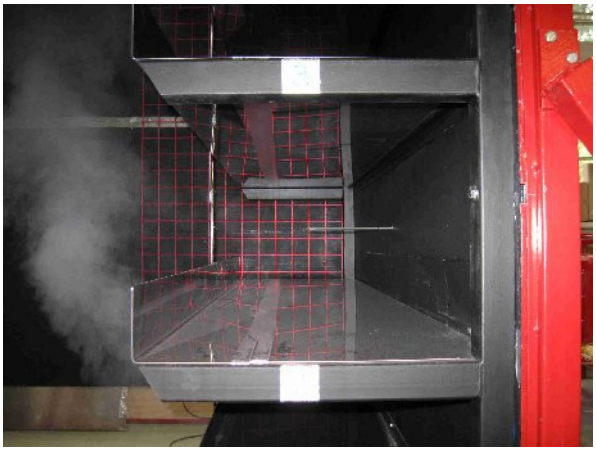
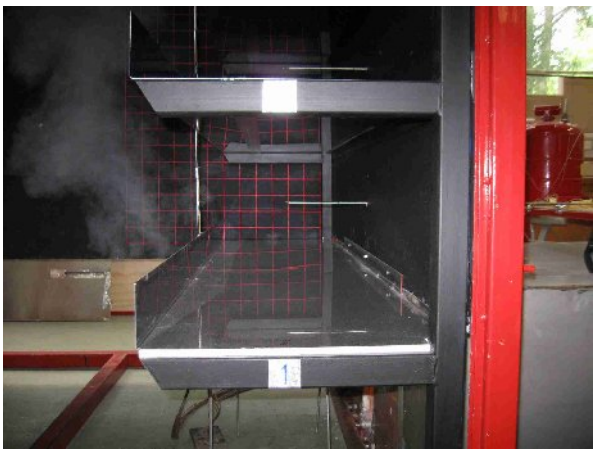
PHOTOGRAPHIC RECORDS

Experiment No. = **10**
Balcony Breadth = **500** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

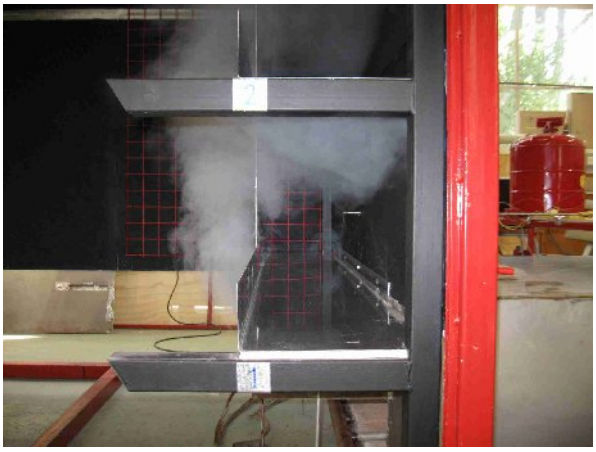
PHOTOGRAPHIC RECORDS

Experiment No. = **13**
Balcony Breadth = **500** **mm**
Plume Width = **200** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

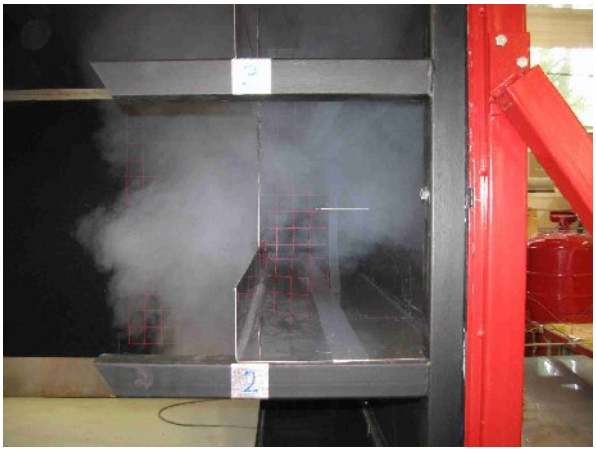
PHOTOGRAPHIC RECORDS

Experiment No. = **16**
Balcony Breadth = **300 mm**
Plume Width = **1000 mm**
Heat Release Rate = **5 kW**

Balcony Level	Photograph
3	
2	
1	

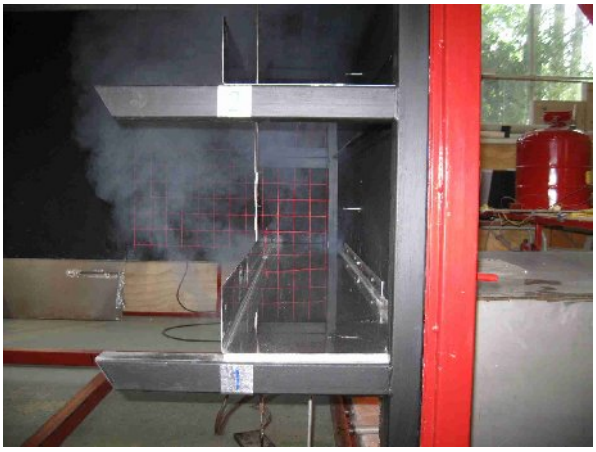
PHOTOGRAPHIC RECORDS

Experiment No. = 17
Balcony Breadth = 300 mm
Plume Width = 1000 mm
Heat Release Rate = 10 kW

Balcony Level	Photograph
3	
2	
1	

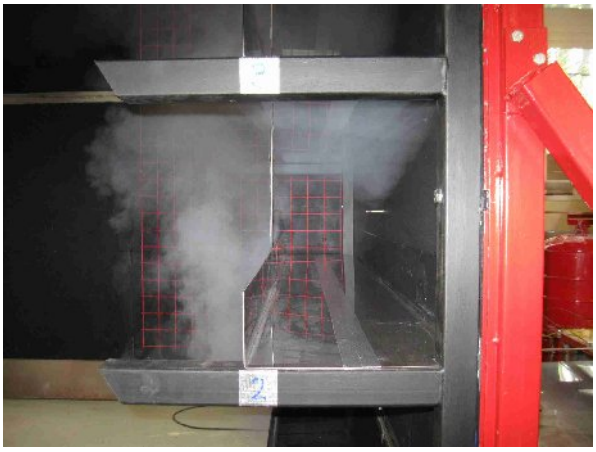
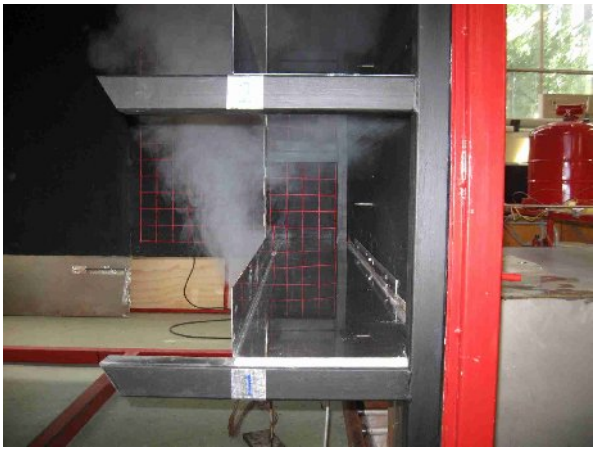
PHOTOGRAPHIC RECORDS

Experiment No. = **18**
Balcony Breadth = **300 mm**
Plume Width = **1000 mm**
Heat Release Rate = **15 kW**

Balcony Level	Photograph
3	
2	
1	

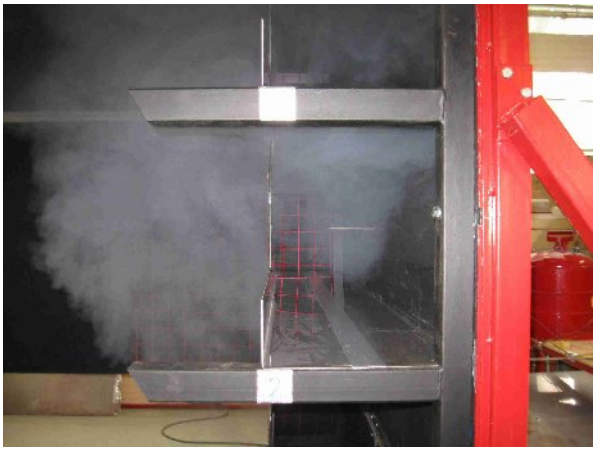
PHOTOGRAPHIC RECORDS

Experiment No. = **19**
Balcony Breadth = **300** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **20**
Balcony Breadth = **300** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

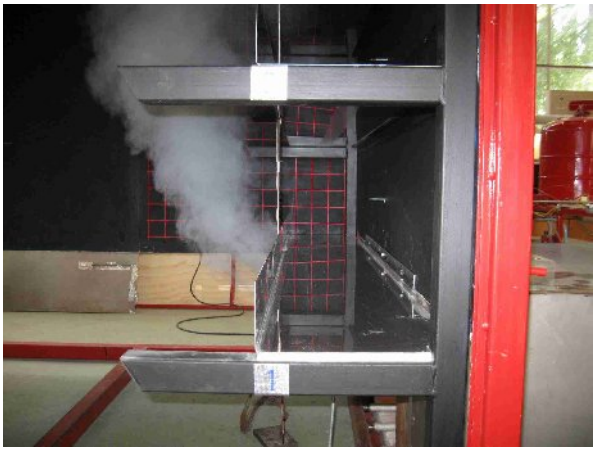
PHOTOGRAPHIC RECORDS

Experiment No. = **21**
Balcony Breadth = **300** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

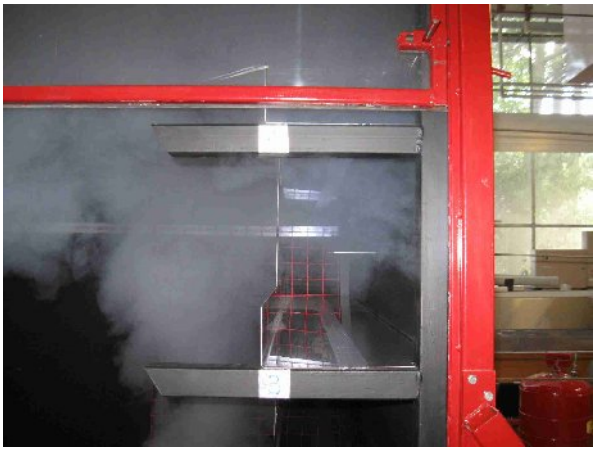
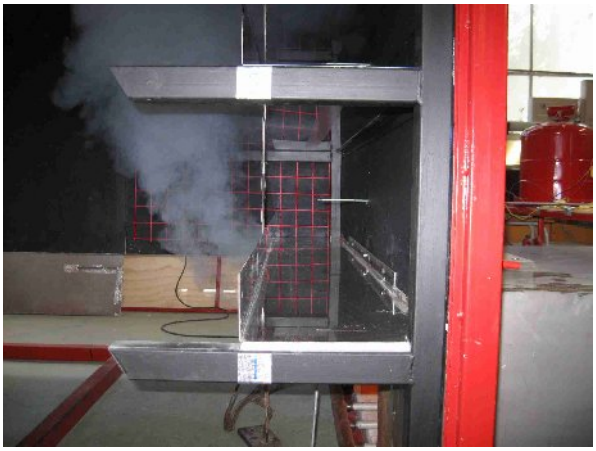
PHOTOGRAPHIC RECORDS

Experiment No. = **22**
Balcony Breadth = **300** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

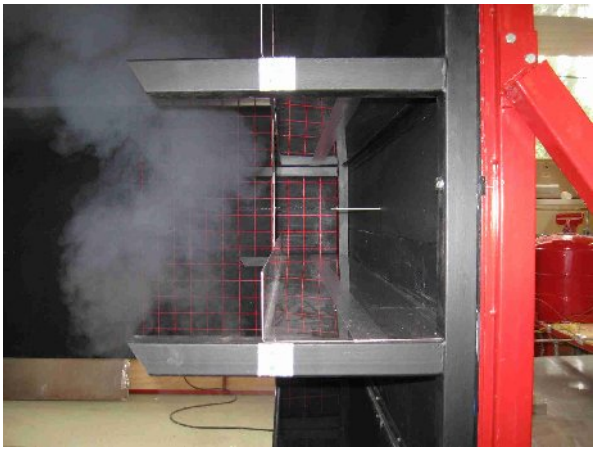
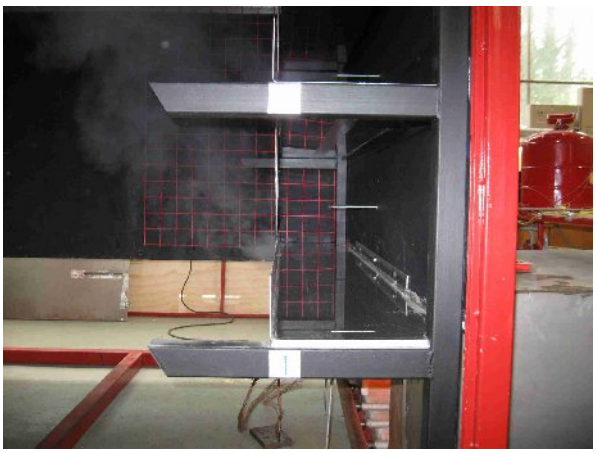
PHOTOGRAPHIC RECORDS

Experiment No. = **23**
Balcony Breadth = **300** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **24**
Balcony Breadth = **300** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

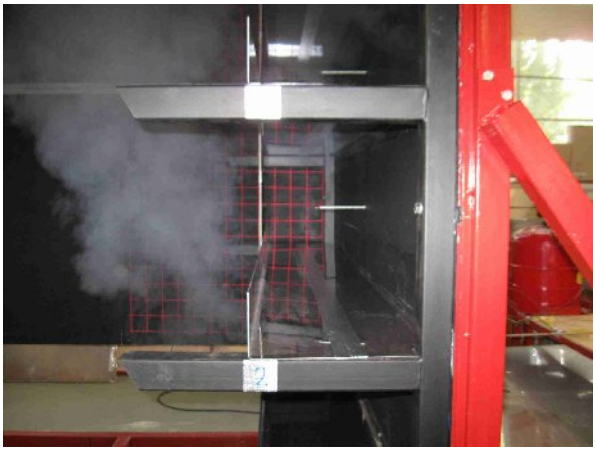
PHOTOGRAPHIC RECORDS

Experiment No. = **25**
Balcony Breadth = **300** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

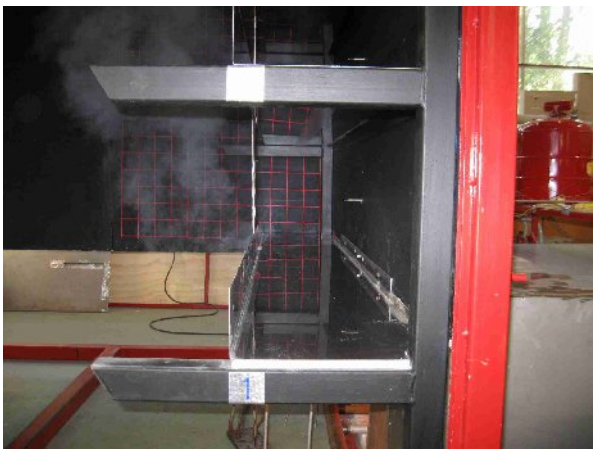
PHOTOGRAPHIC RECORDS

Experiment No. = **26**
Balcony Breadth = **300 mm**
Plume Width = **400 mm**
Heat Release Rate = **10 kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **27**
Balcony Breadth = **300** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **28**
Balcony Breadth = **300** **mm**
Plume Width = **200** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **31**
Balcony Breadth = **200 mm**
Plume Width = **1000 mm**
Heat Release Rate = **5 kW**

Balcony Level	Photograph
3	
2	
1	

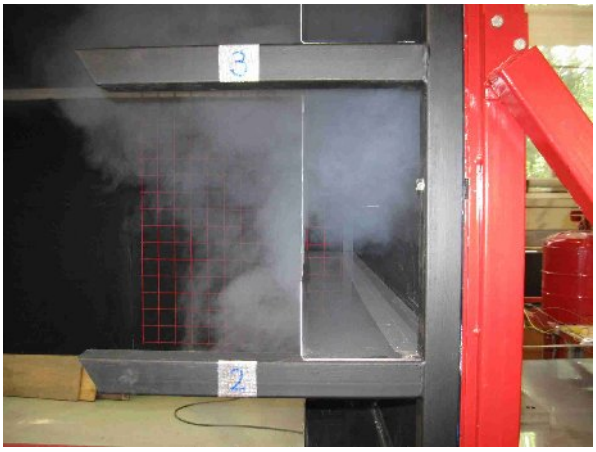
PHOTOGRAPHIC RECORDS

Experiment No. = **32**
Balcony Breadth = **200 mm**
Plume Width = **1000 mm**
Heat Release Rate = **10 kW**

Balcony Level	Photograph
3	
2	
1	

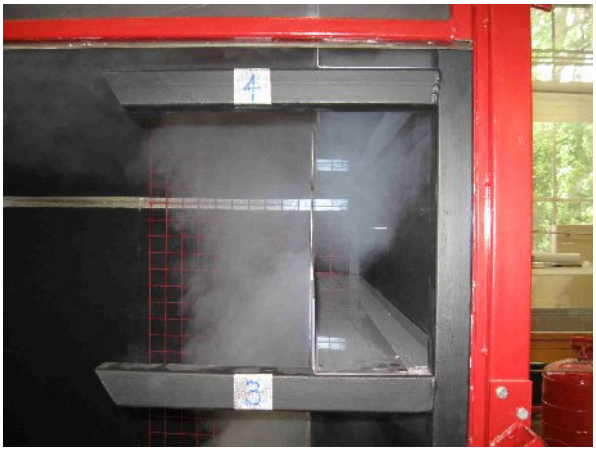
PHOTOGRAPHIC RECORDS

Experiment No. = **33**
Balcony Breadth = **200 mm**
Plume Width = **1000 mm**
Heat Release Rate = **15 kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **34**
Balcony Breadth = **200** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **35**
Balcony Breadth = **200** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **36**
Balcony Breadth = **200** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **37**
Balcony Breadth = **200** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **38**
Balcony Breadth = **200** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

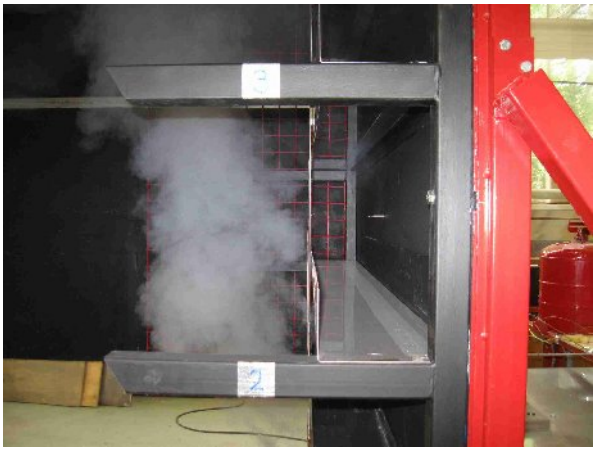
PHOTOGRAPHIC RECORDS

Experiment No. = **39**
Balcony Breadth = **200** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **40**
Balcony Breadth = **200** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **41**
Balcony Breadth = **200** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

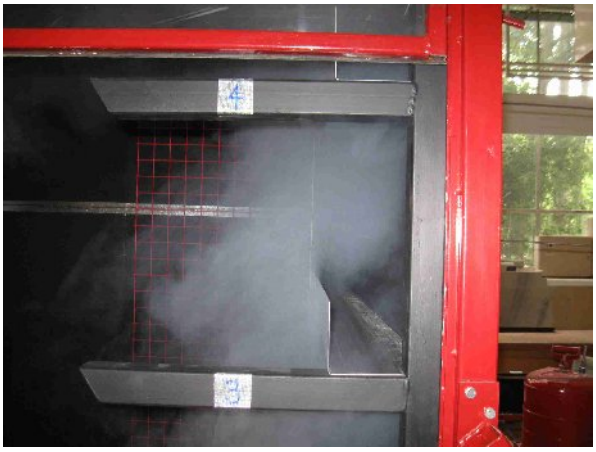
PHOTOGRAPHIC RECORDS

Experiment No. = **43**
Balcony Breadth = **200** **mm**
Plume Width = **200** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **46**
Balcony Breadth = **150 mm**
Plume Width = **1000 mm**
Heat Release Rate = **5 kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **47**
Balcony Breadth = **150 mm**
Plume Width = **1000 mm**
Heat Release Rate = **10 kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **48**
Balcony Breadth = **150 mm**
Plume Width = **1000 mm**
Heat Release Rate = **15 kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **49**
Balcony Breadth = **150** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

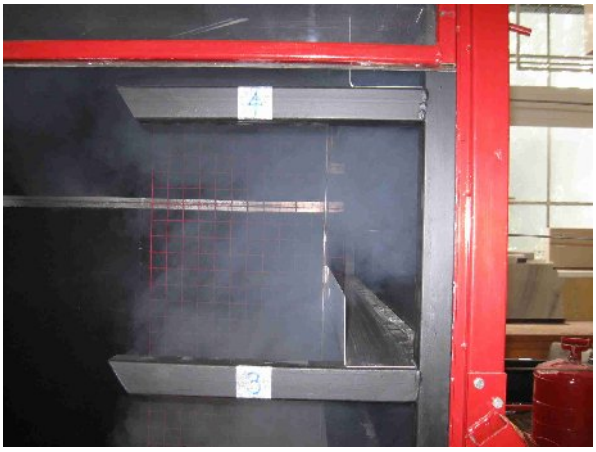
PHOTOGRAPHIC RECORDS

Experiment No. = **50**
Balcony Breadth = **150** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **10** **kW**

Balcony Level	Photograph
3	
2	
1	

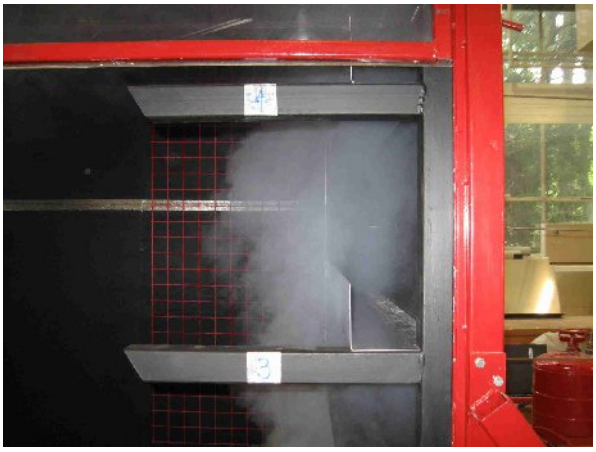
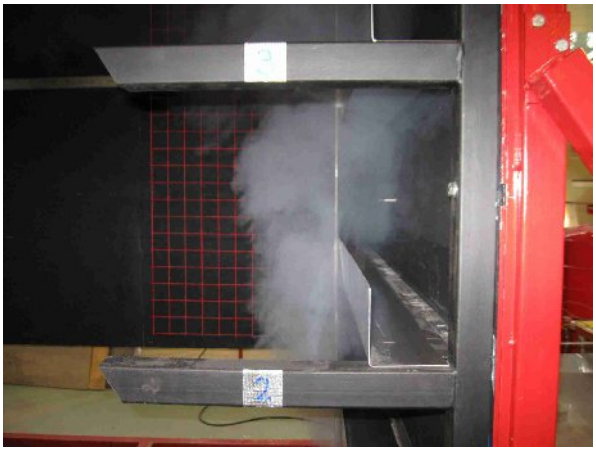
PHOTOGRAPHIC RECORDS

Experiment No. = **51**
Balcony Breadth = **150** **mm**
Plume Width = **800** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **52**
Balcony Breadth = **150** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

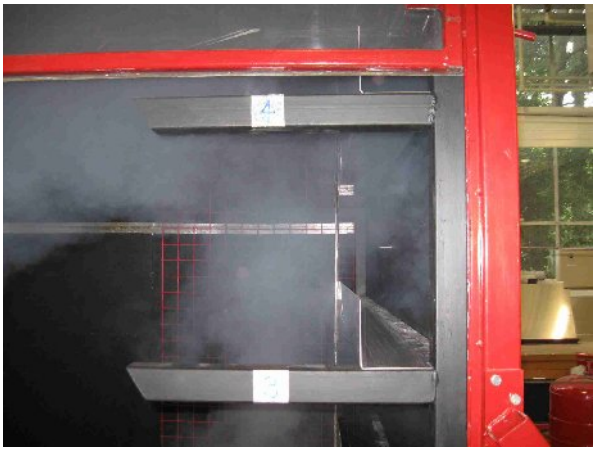
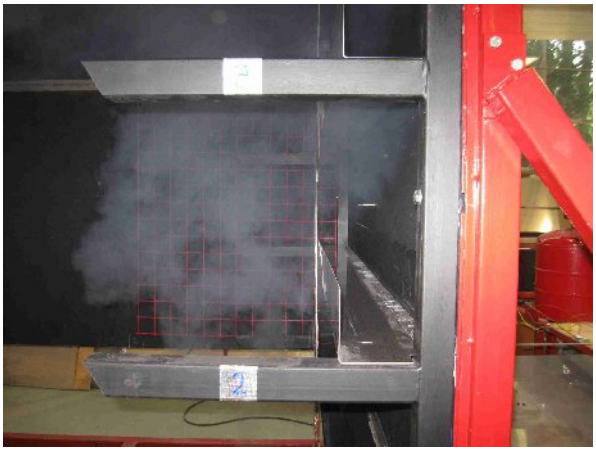
PHOTOGRAPHIC RECORDS

Experiment No. = 53
Balcony Breadth = 150 mm
Plume Width = 600 mm
Heat Release Rate = 10 kW

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **54**
Balcony Breadth = **150** **mm**
Plume Width = **600** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **55**
Balcony Breadth = **150** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = 56
Balcony Breadth = 150 mm
Plume Width = 400 mm
Heat Release Rate = 10 kW

Balcony Level	Photograph
3	
2	
1	

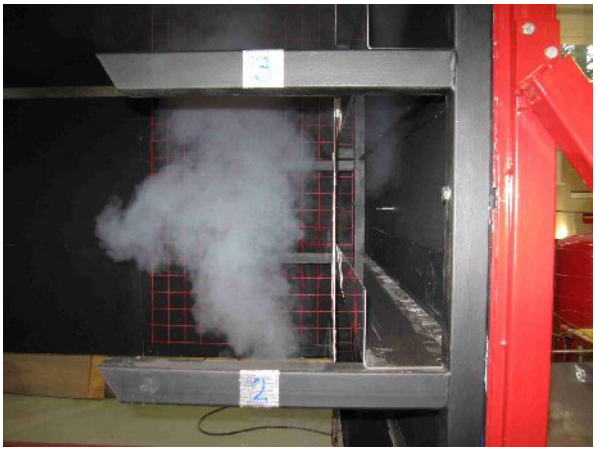
PHOTOGRAPHIC RECORDS

Experiment No. = **57**
Balcony Breadth = **150** **mm**
Plume Width = **400** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **58**
Balcony Breadth = **150** **mm**
Plume Width = **200** **mm**
Heat Release Rate = **5** **kW**

Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

Experiment No. = **59**
Balcony Breadth = **150** **mm**
Plume Width = **200** **mm**
Heat Release Rate = **10** **kW**

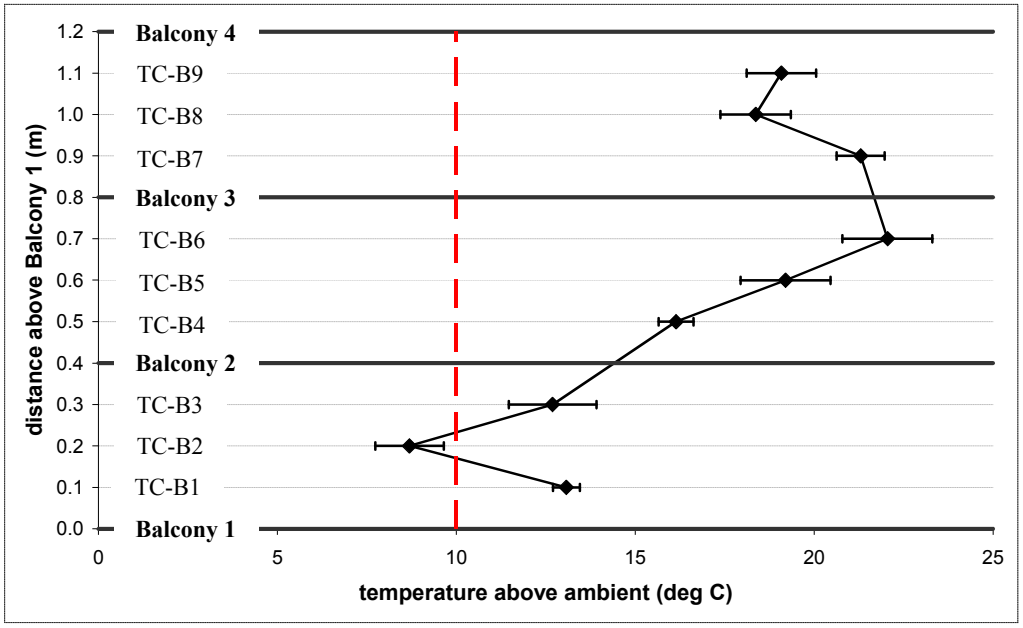
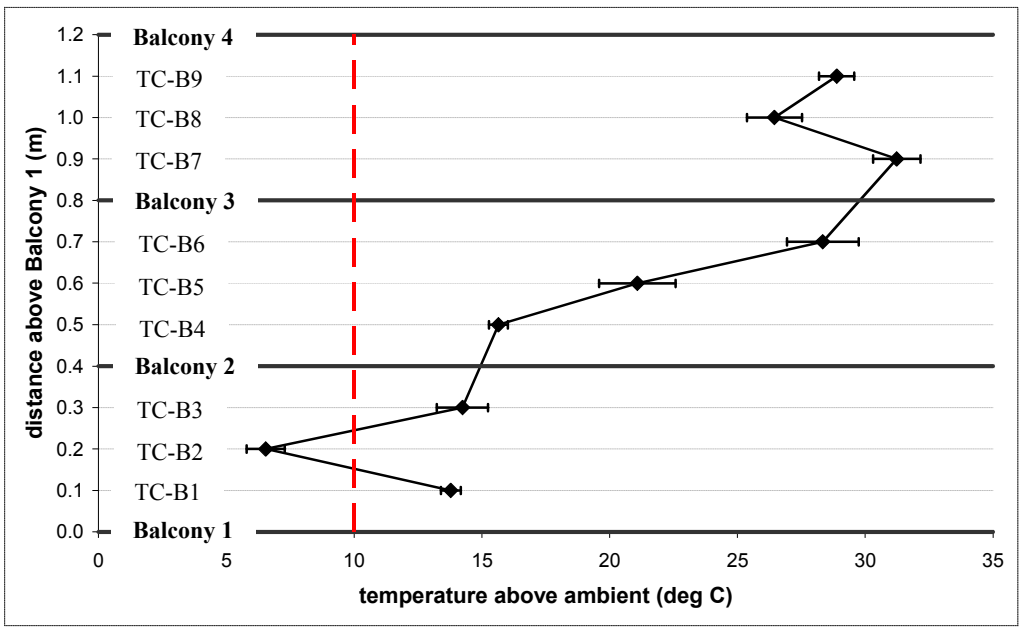
Balcony Level	Photograph
3	
2	
1	

PHOTOGRAPHIC RECORDS

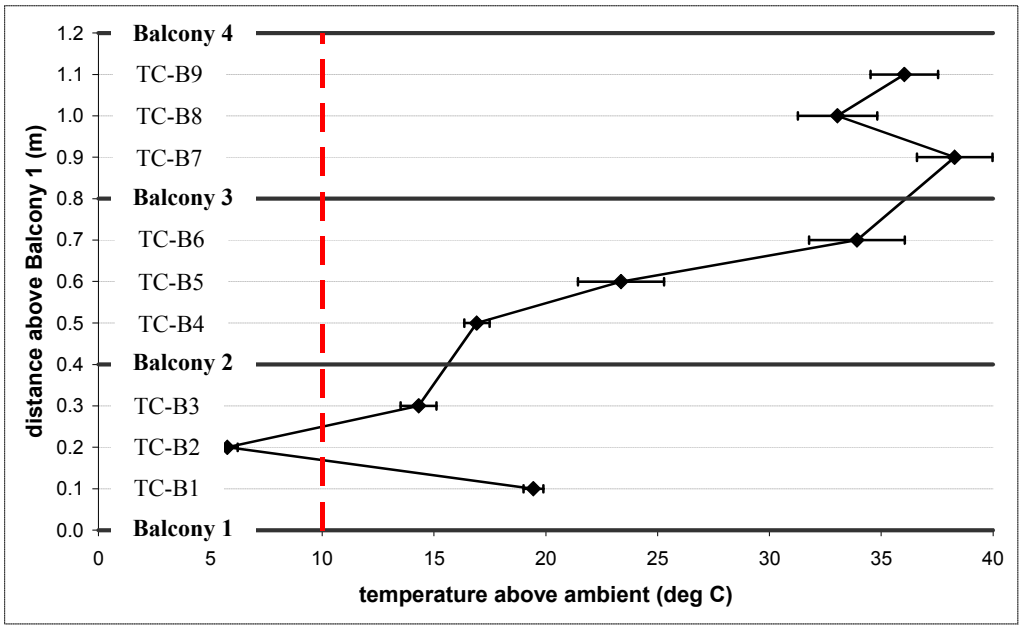
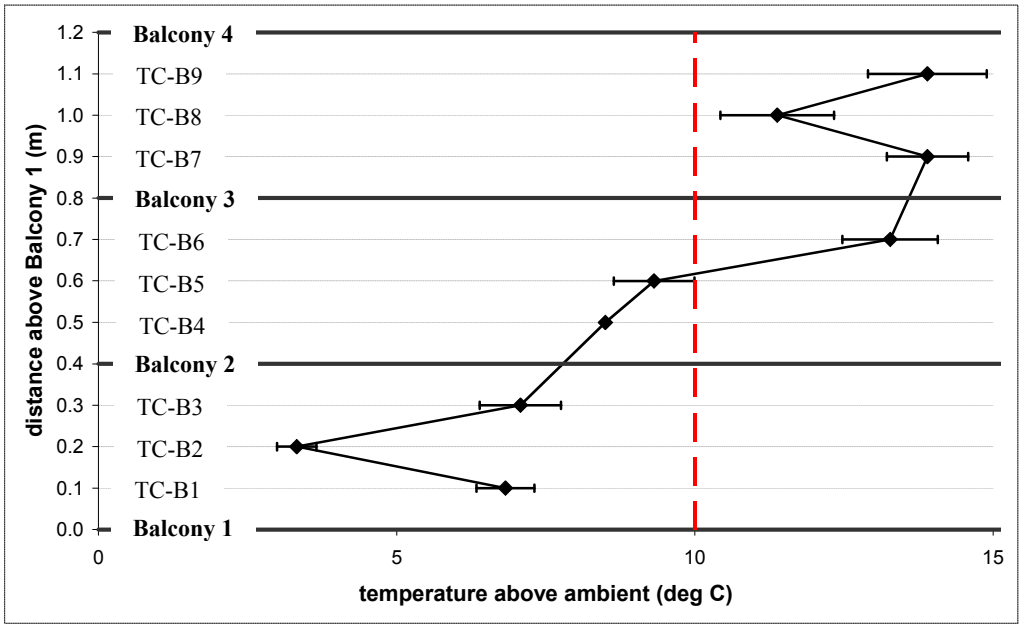
Experiment No. = **60**
Balcony Breadth = **150** **mm**
Plume Width = **200** **mm**
Heat Release Rate = **15** **kW**

Balcony Level	Photograph
3	
2	
1	

TEMPERATURE PROFILES ACROSS BALCONY EDGE

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure C-1: Experiment 1	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure C-2: Experiment 2	

TEMPERATURE PROFILES ACROSS BALCONY EDGE

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure C-3: Experiment 3	
	✓✓ Balcony 3 ✓ Balcony 2 ✘ Balcony 1
Figure C-4: Experiment 4	

TEMPERATURE PROFILES ACROSS BALCONY EDGE

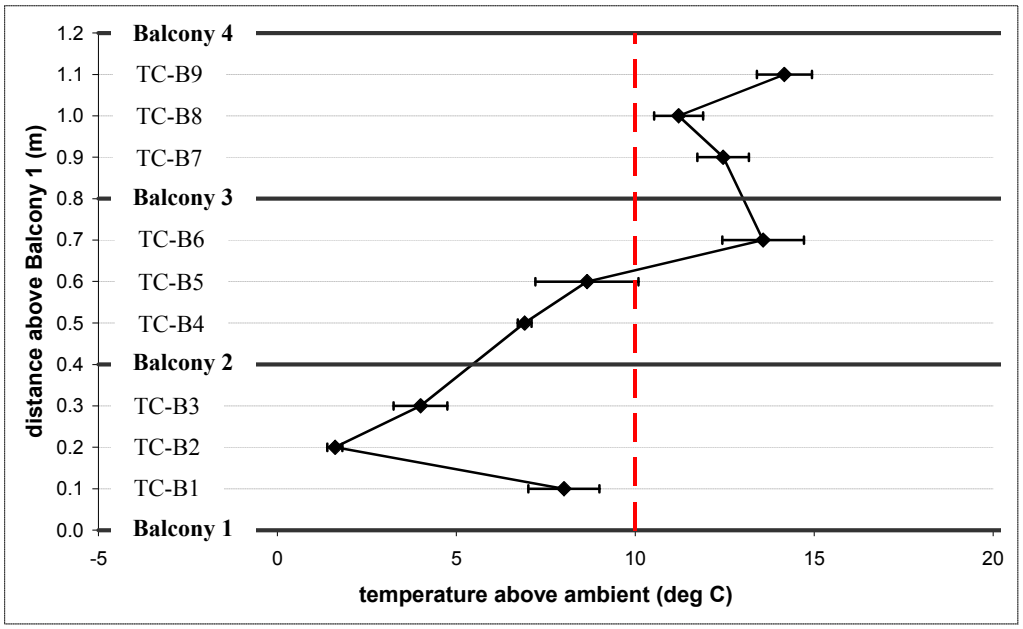
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓ Balcony 2 ✗ Balcony 1

Figure C-5: Experiment 5

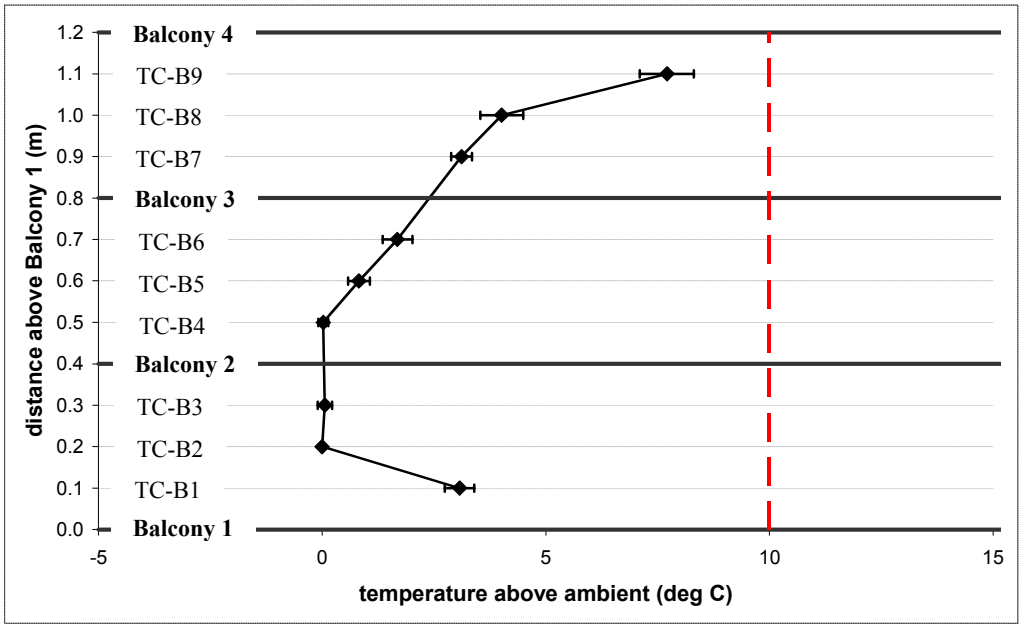
	✓✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-6: Experiment 6

TEMPERATURE PROFILES ACROSS BALCONY EDGE

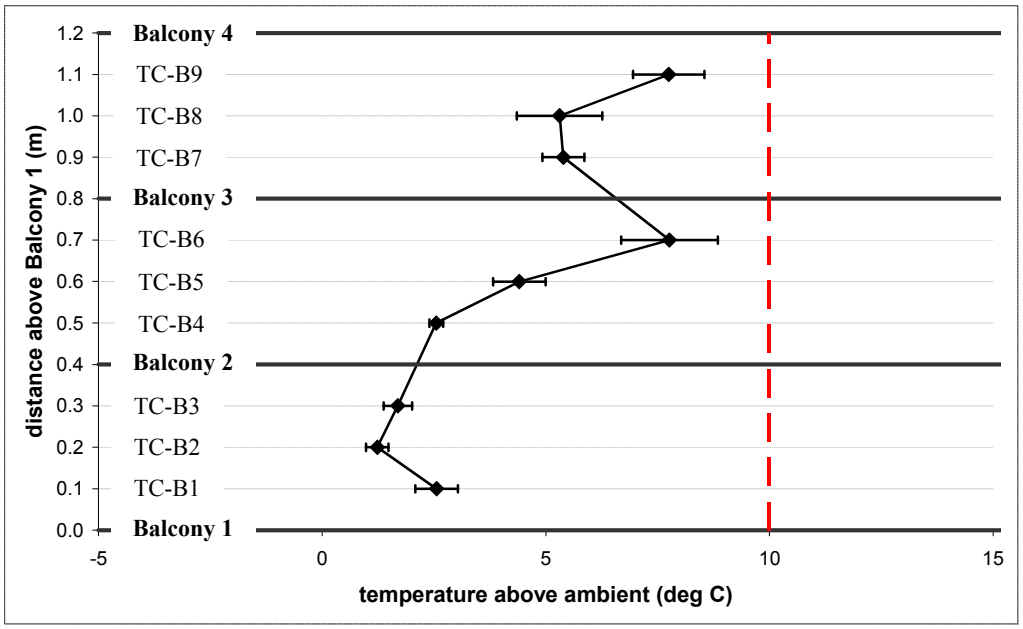
Temperature Profiles	Visual Observations
	

Figure C-7: Experiment 7

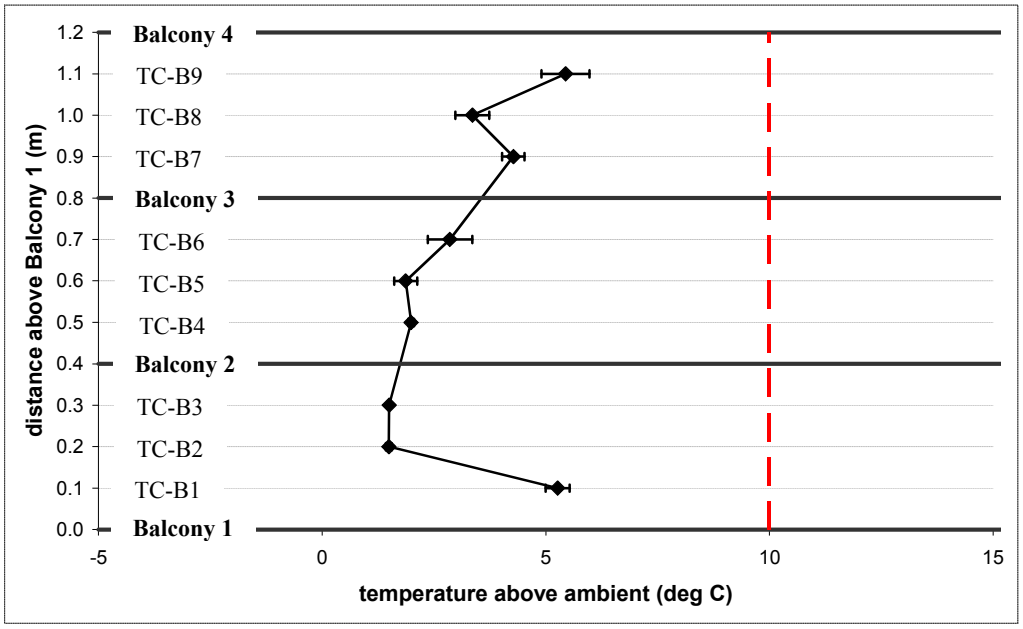


Figure C-8: Experiment 8

TEMPERATURE PROFILES ACROSS BALCONY EDGE

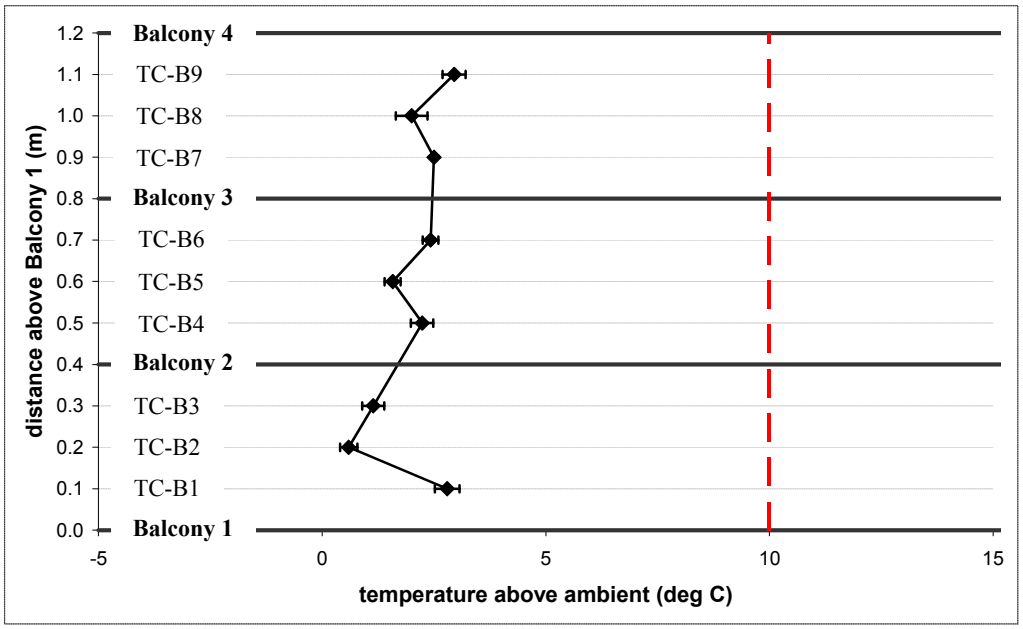
Temperature Profiles	Visual Observations
	

Figure C-9: Experiment 10

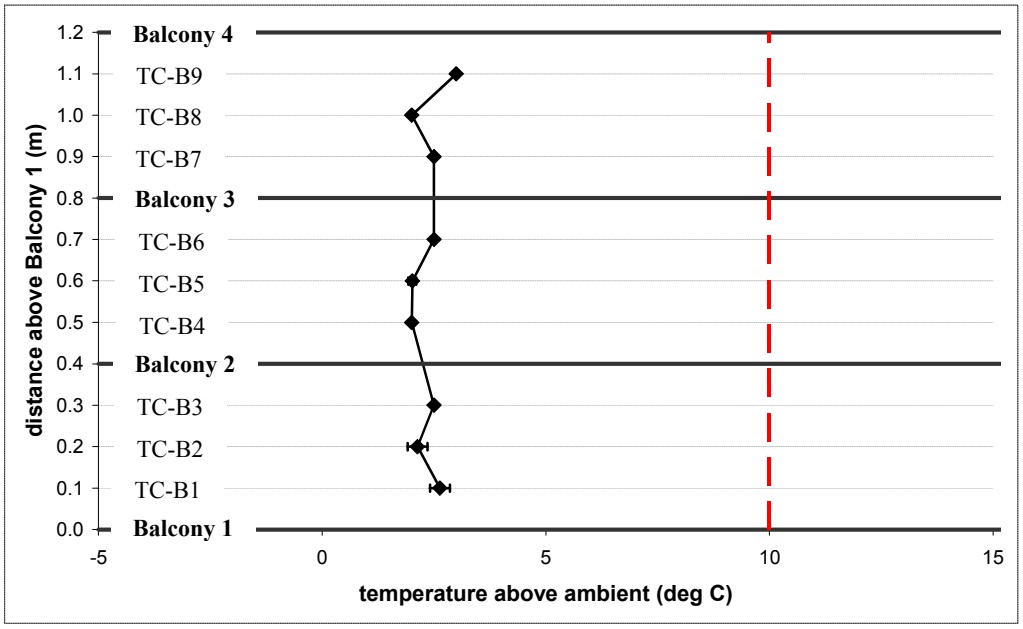


Figure C-10: Experiment 13

TEMPERATURE PROFILES ACROSS BALCONY EDGE

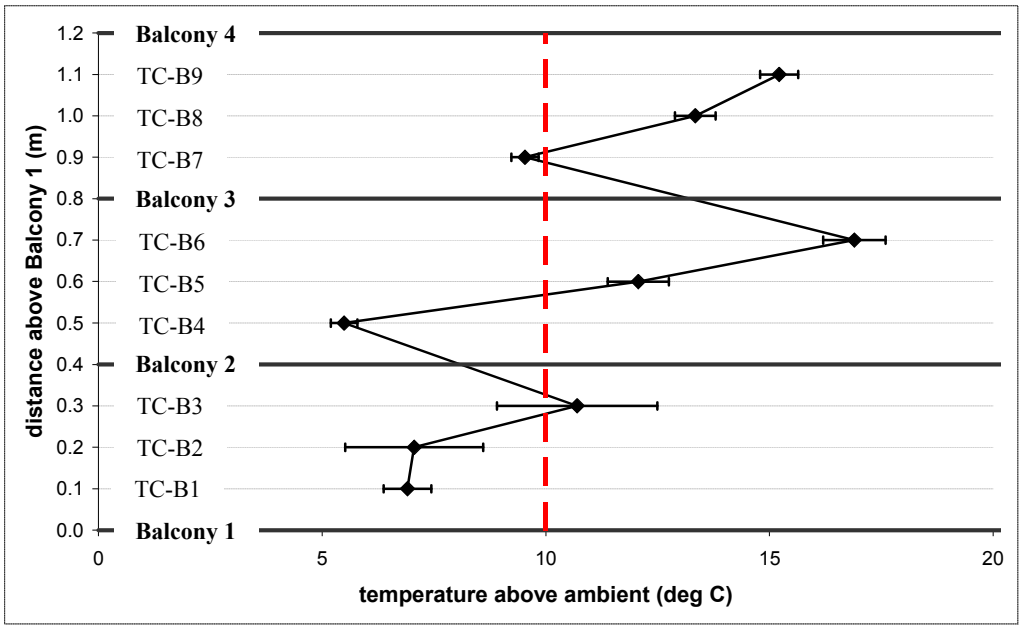
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-11: Experiment 16

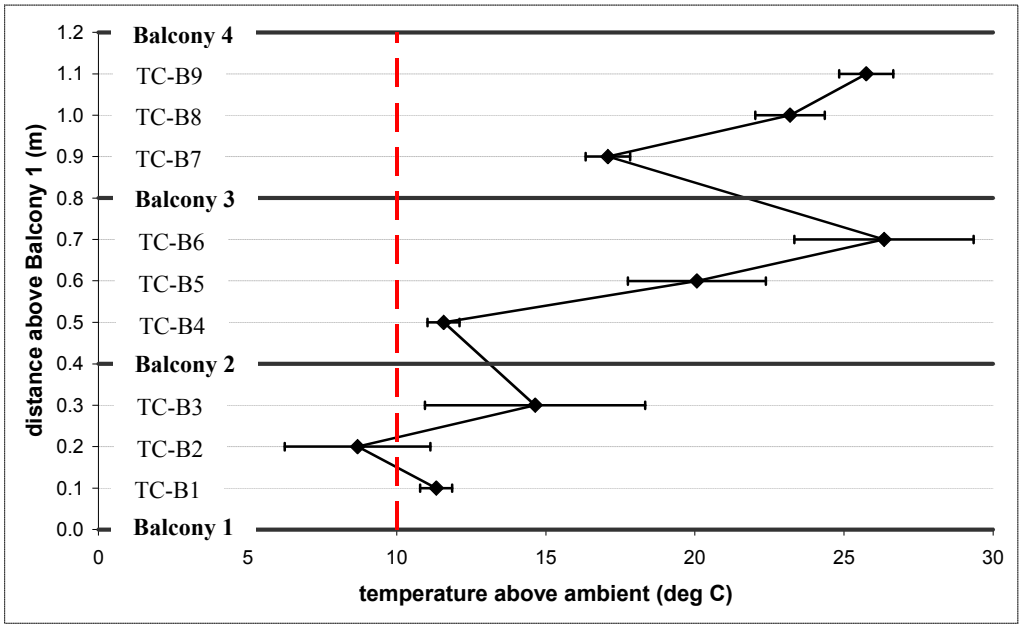
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-12: Experiment 17

TEMPERATURE PROFILES ACROSS BALCONY EDGE

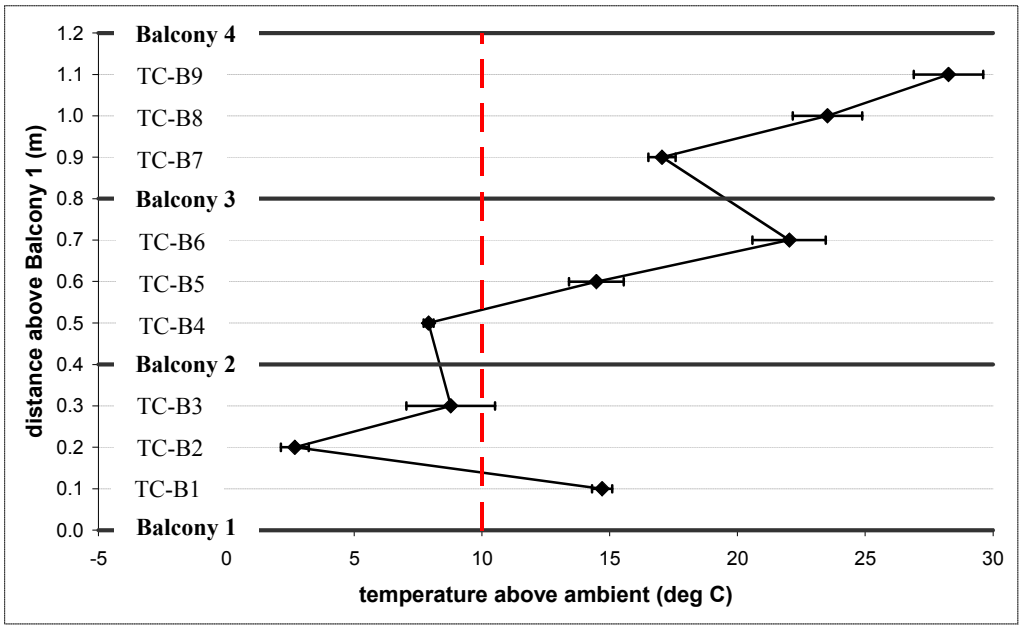
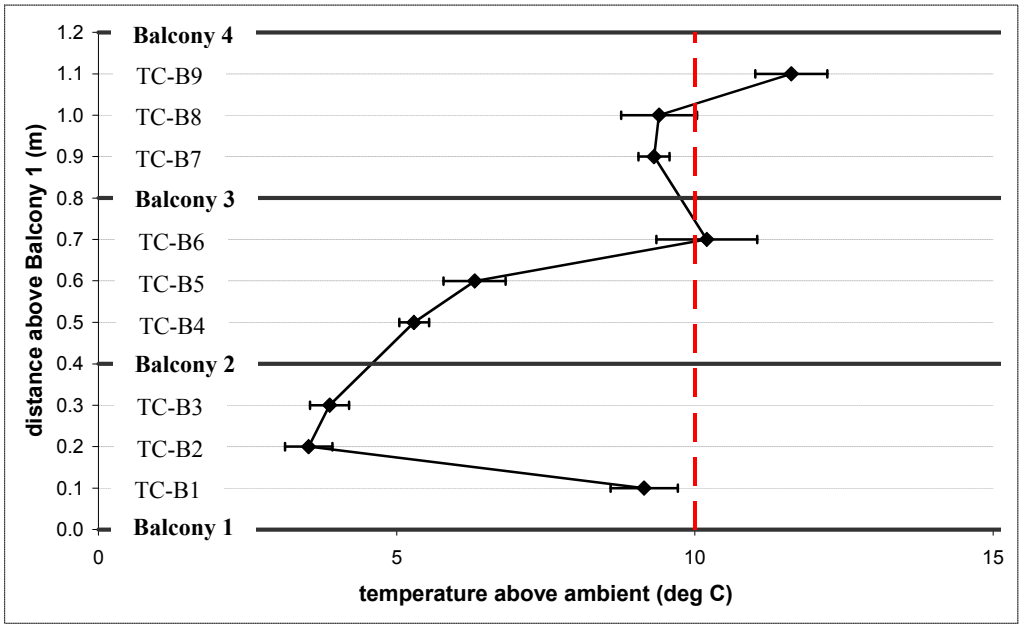
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-13: Experiment 18



✓✓ Balcony 3
✓ Balcony 2
✓ Balcony 1

Figure C-14: Experiment 19

TEMPERATURE PROFILES ACROSS BALCONY EDGE

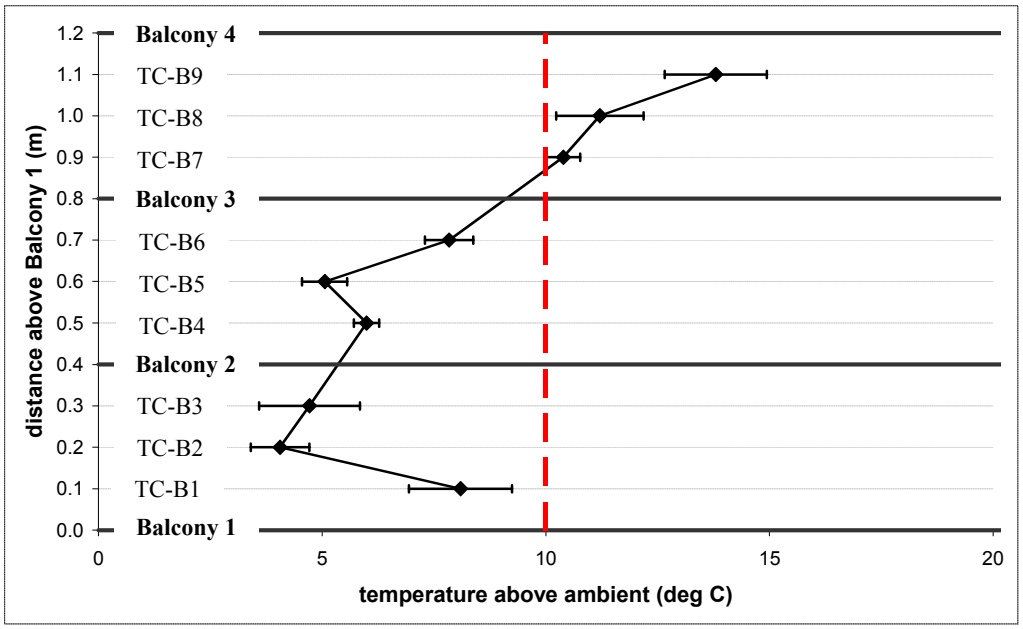
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-15: Experiment 20

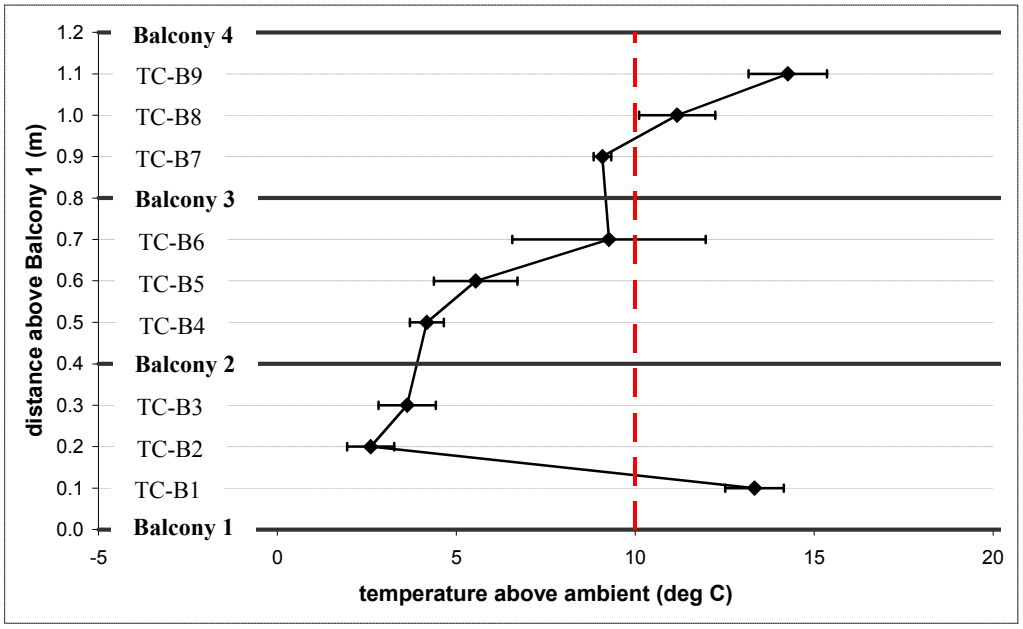
	✓✓ Balcony 3 ✓ Balcony 2 ✘ Balcony 1

Figure C-16: Experiment 21

TEMPERATURE PROFILES ACROSS BALCONY EDGE

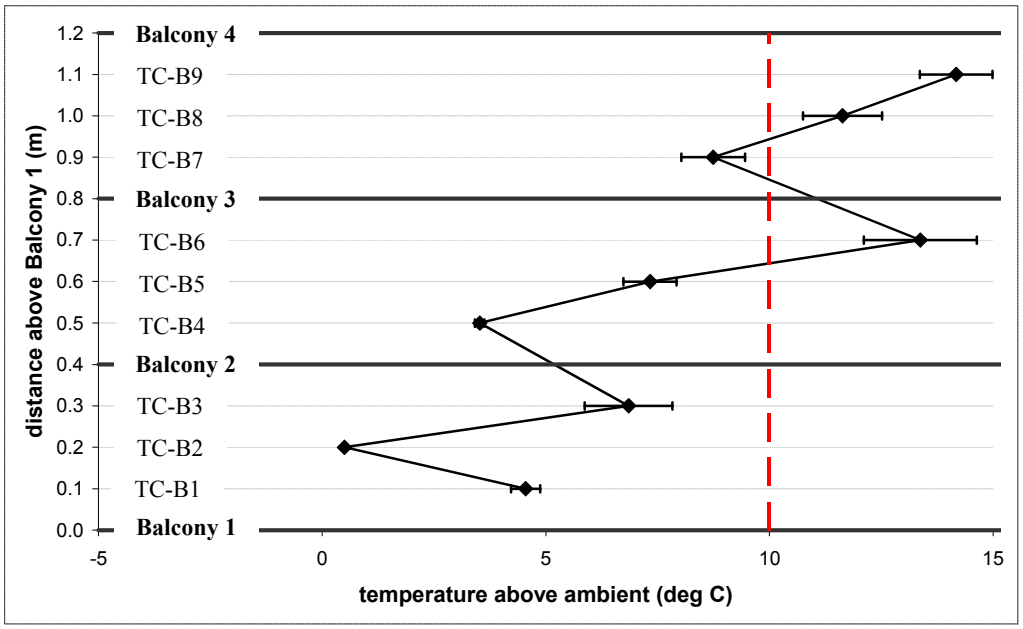
Temperature Profiles	Visual Observations
	

Figure C-17: Experiment 22

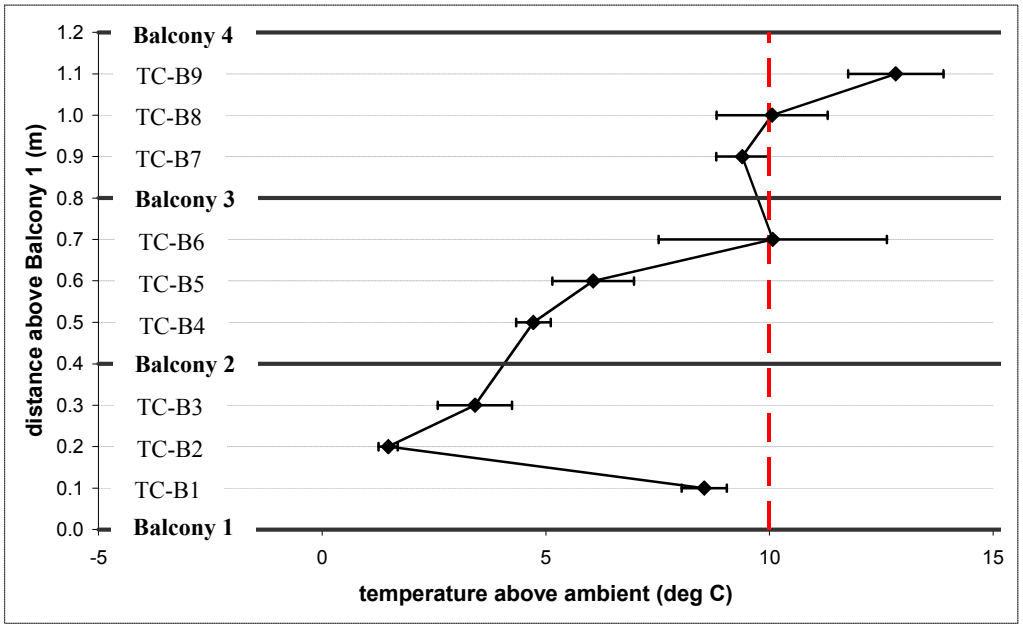


Figure C-18: Experiment 23

TEMPERATURE PROFILES ACROSS BALCONY EDGE

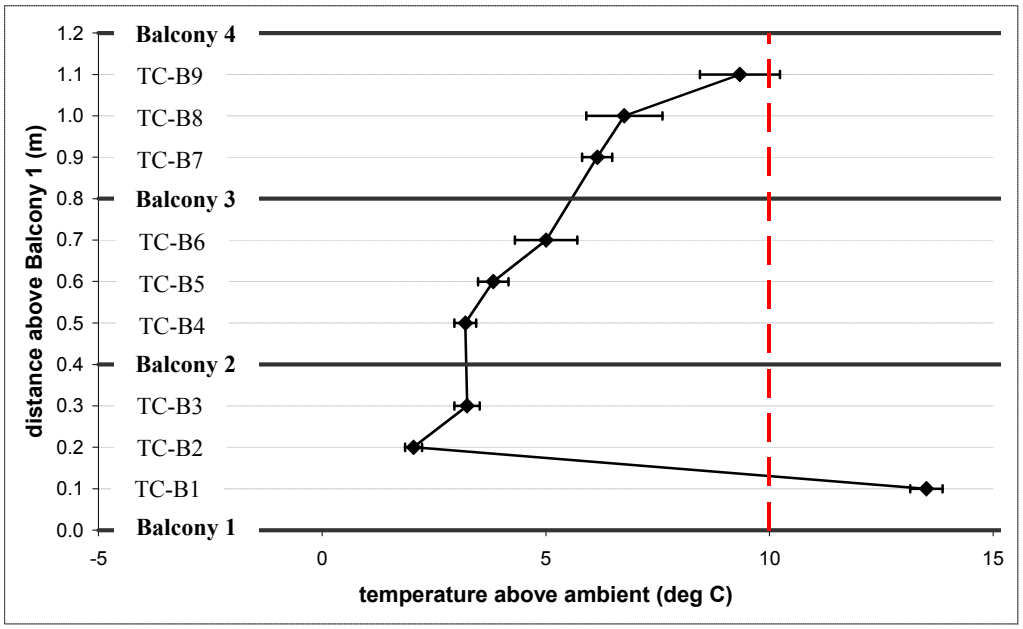
Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-19: Experiment 24

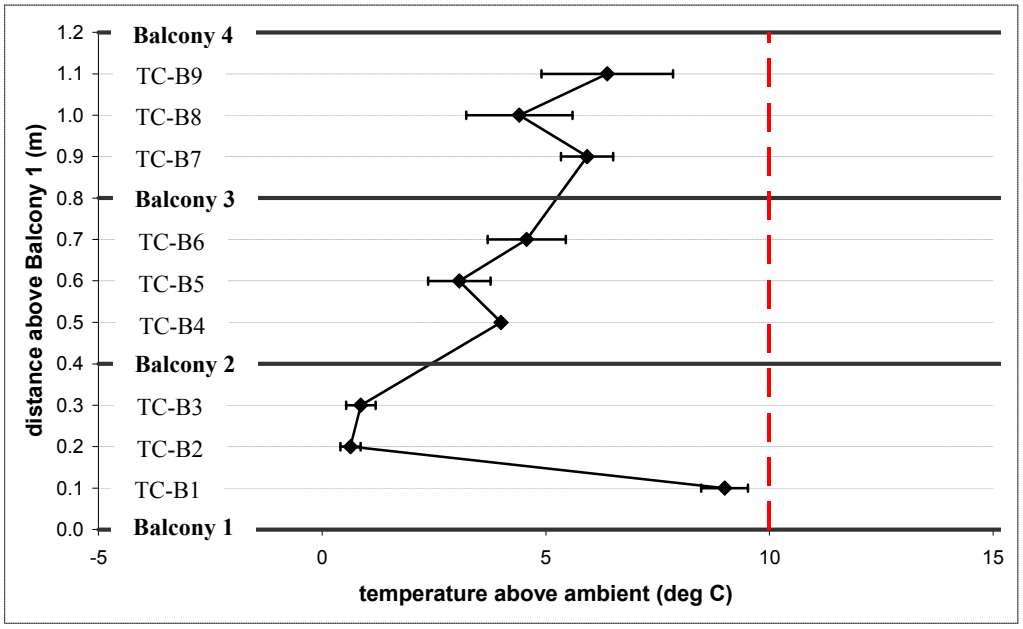
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-20: Experiment 25

TEMPERATURE PROFILES ACROSS BALCONY EDGE

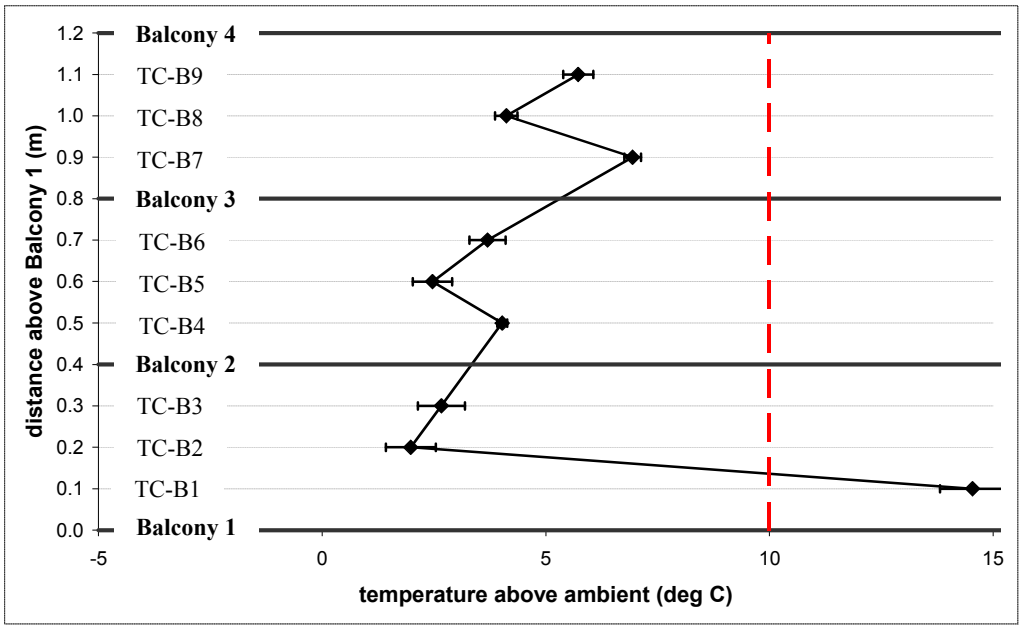
Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-21: Experiment 26

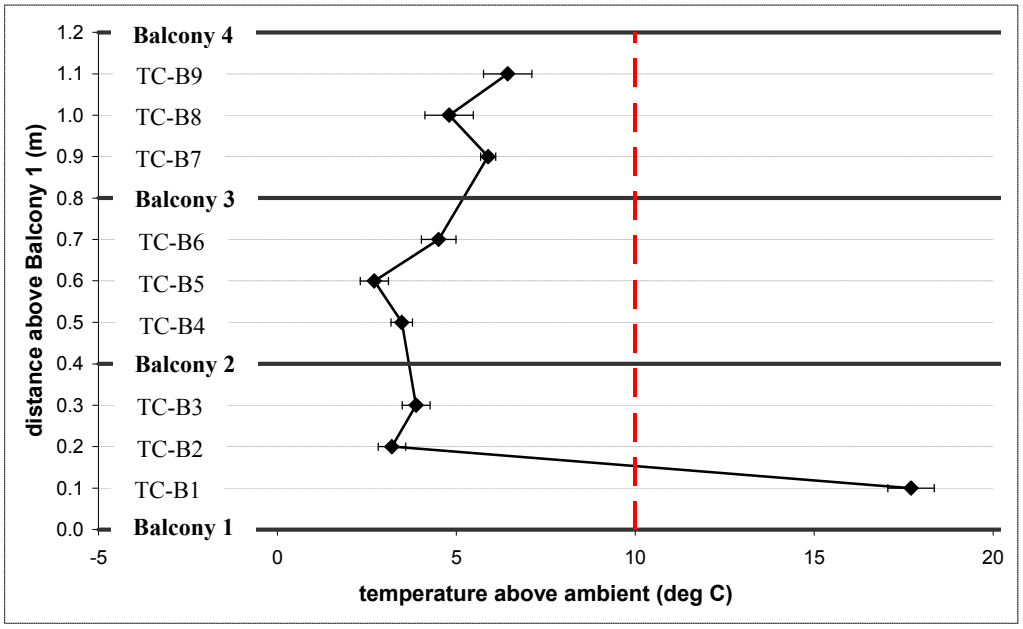
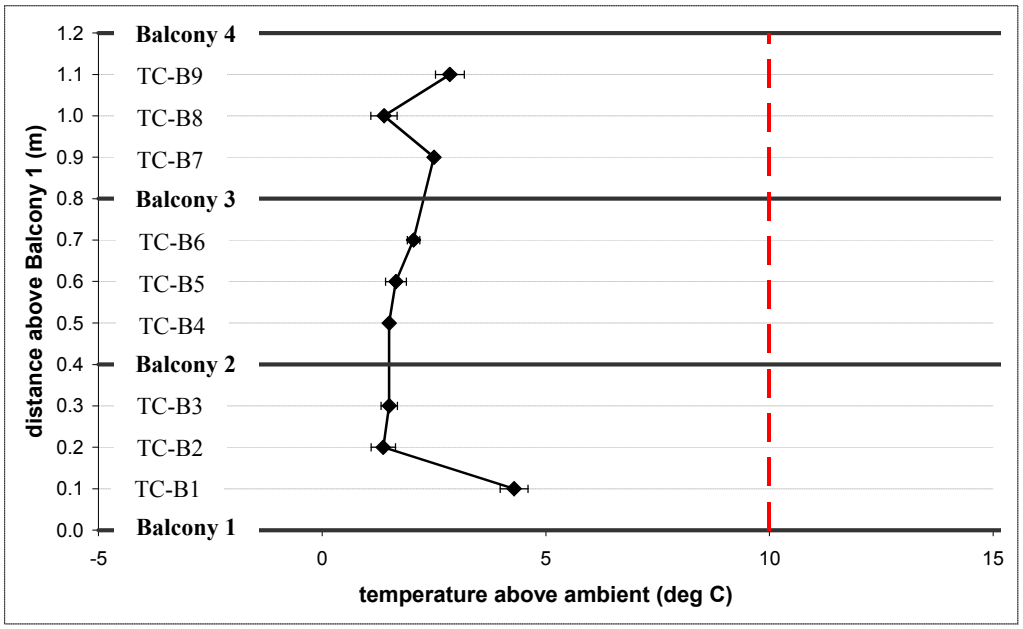
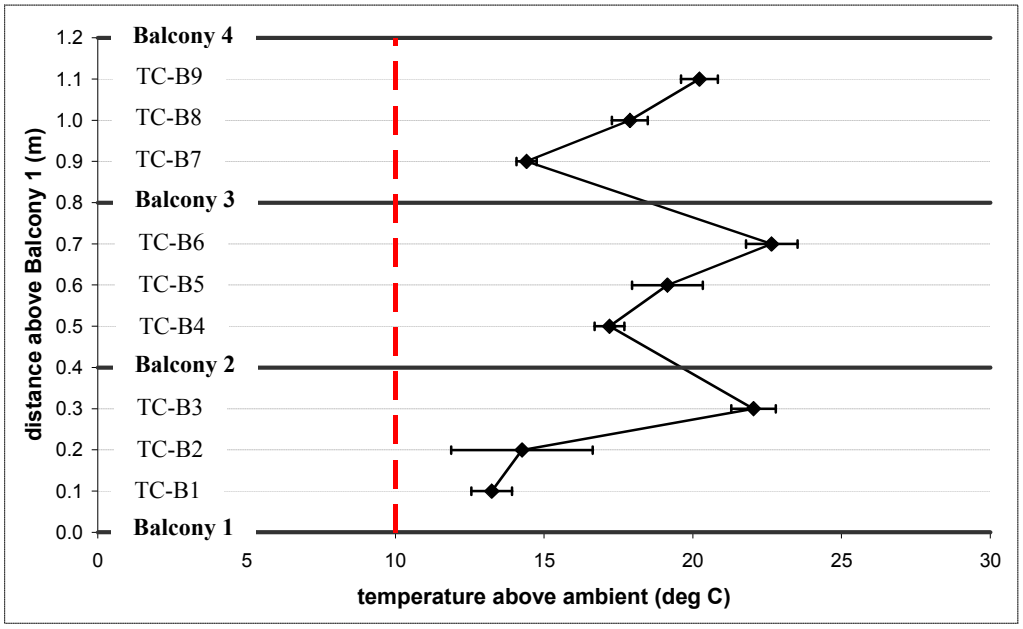
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-22: Experiment 27

TEMPERATURE PROFILES ACROSS BALCONY EDGE

Temperature Profiles	Visual Observations
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure C-23: Experiment 28	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1
Figure C-24: Experiment 31	

TEMPERATURE PROFILES ACROSS BALCONY EDGE

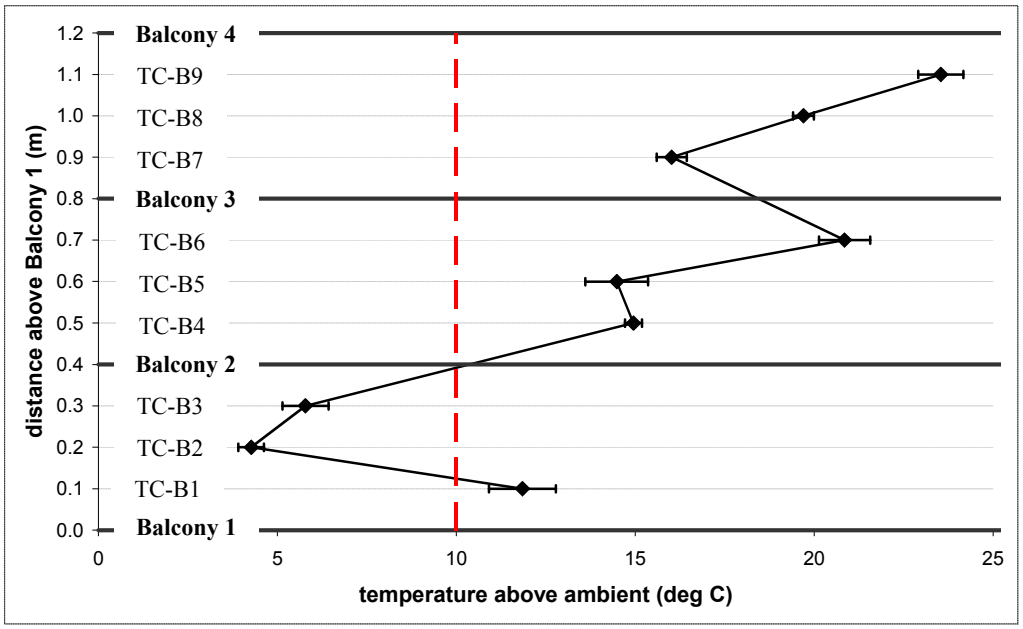
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-25: Experiment 32

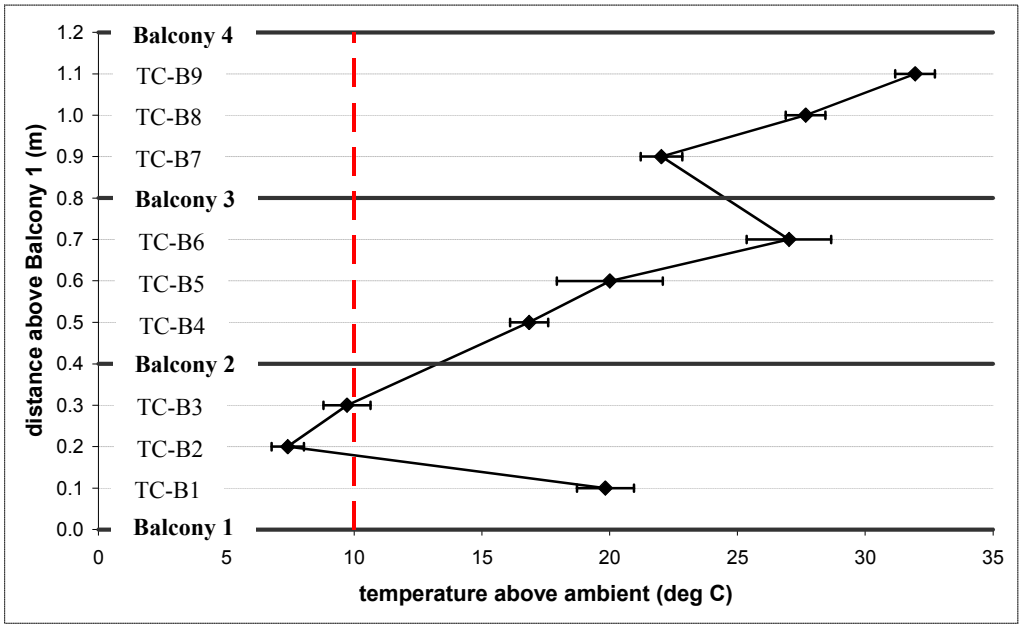
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1

Figure C-26: Experiment 33

TEMPERATURE PROFILES ACROSS BALCONY EDGE

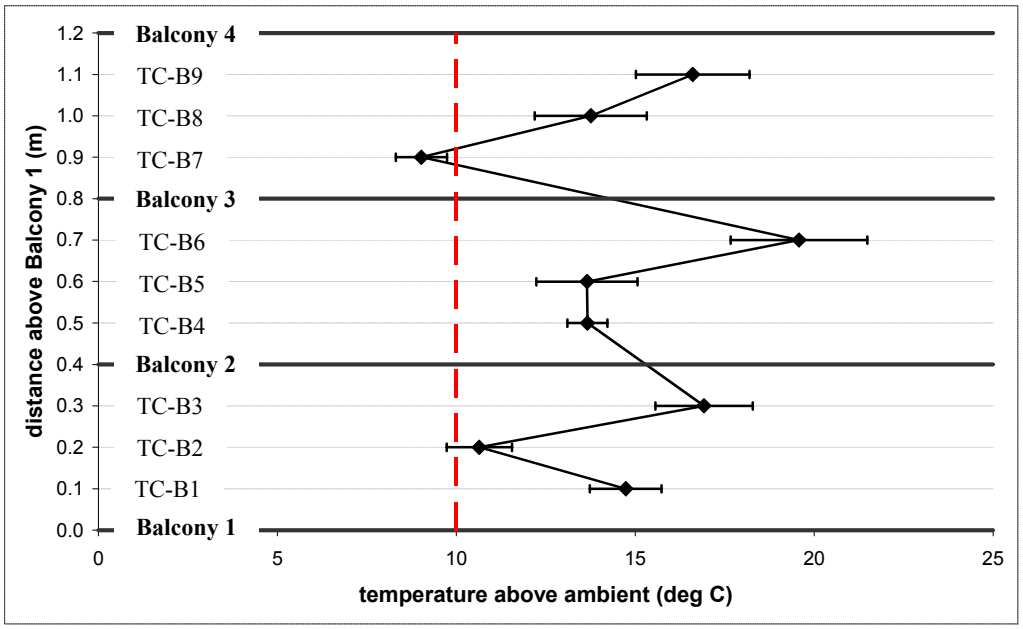
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1

Figure C-27: Experiment 34

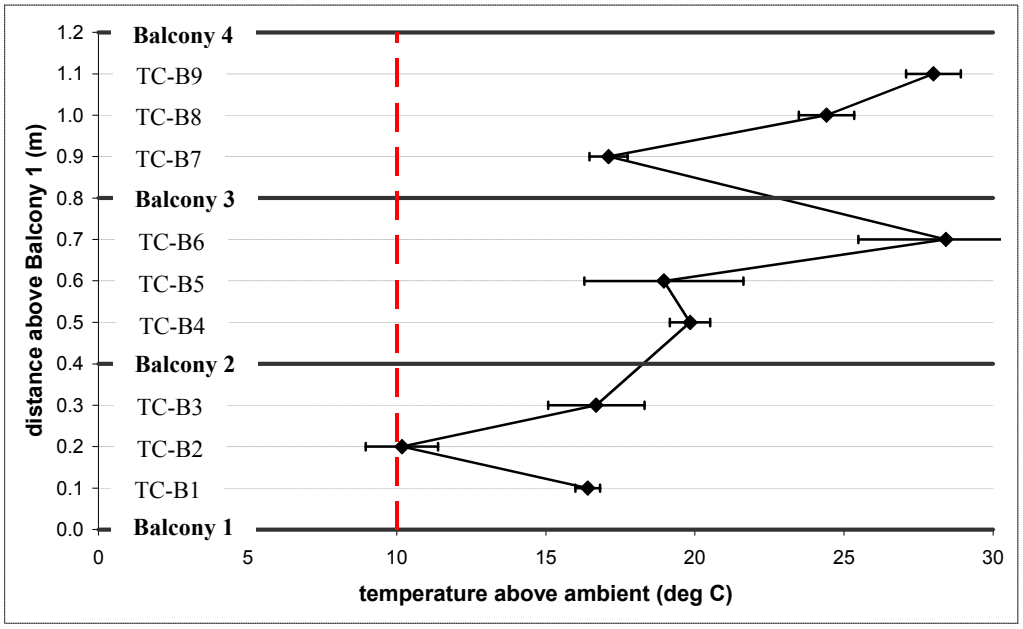
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-28: Experiment 35

TEMPERATURE PROFILES ACROSS BALCONY EDGE

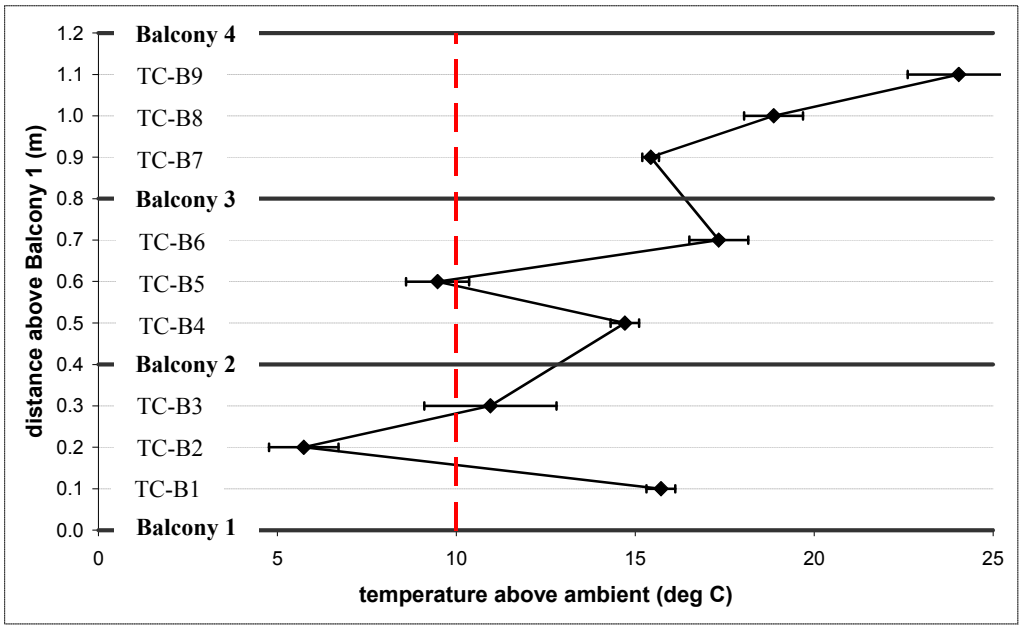
Temperature Profiles	Visual Observations
	

Figure C-29: Experiment 36

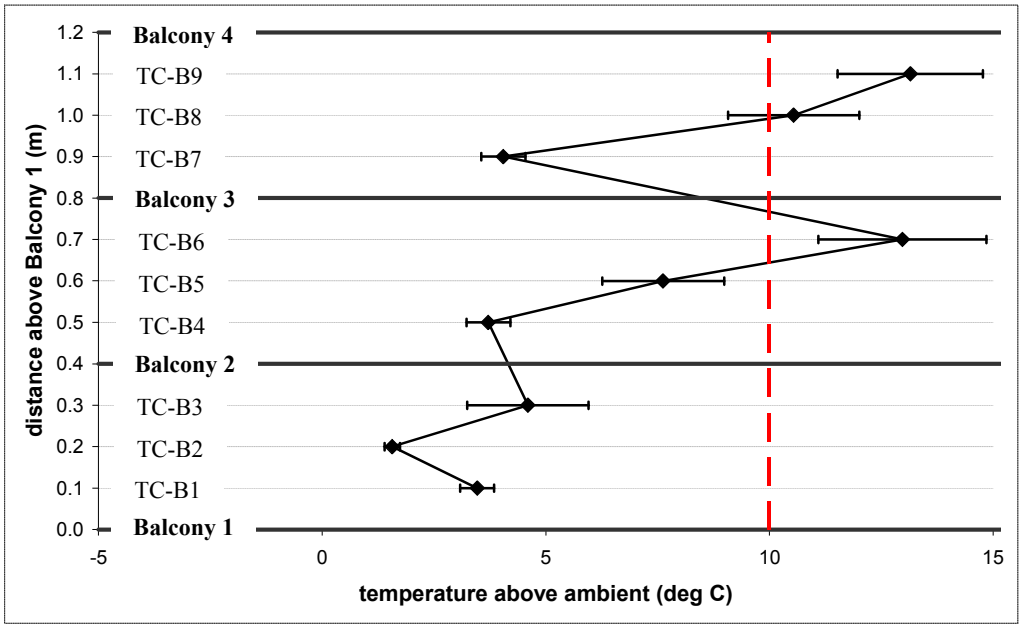


Figure C-30: Experiment 37

TEMPERATURE PROFILES ACROSS BALCONY EDGE

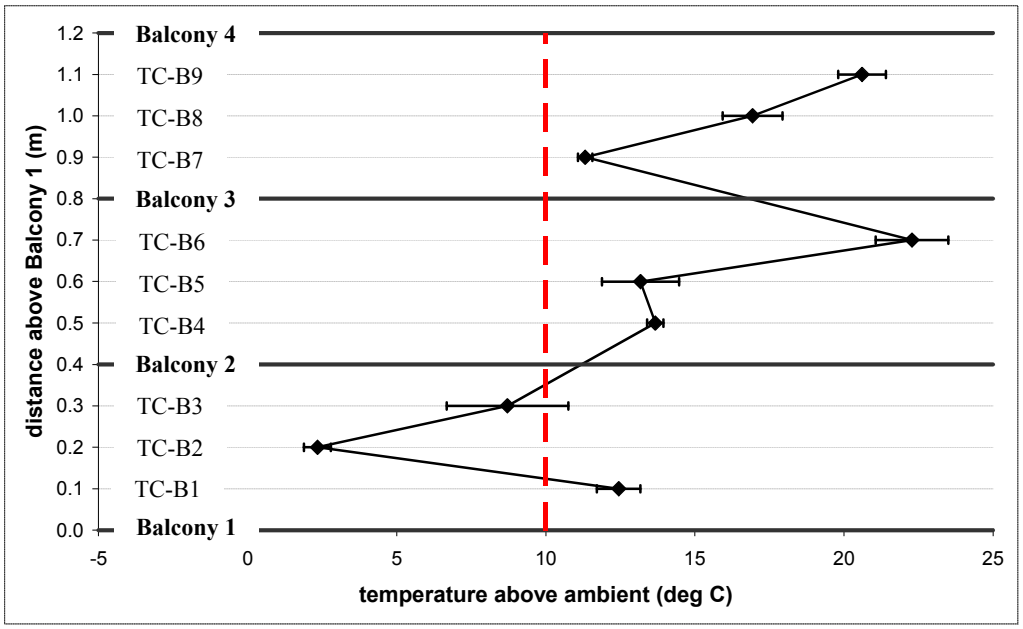
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓ Balcony 2 ✓ Balcony 1

Figure C-31: Experiment 38

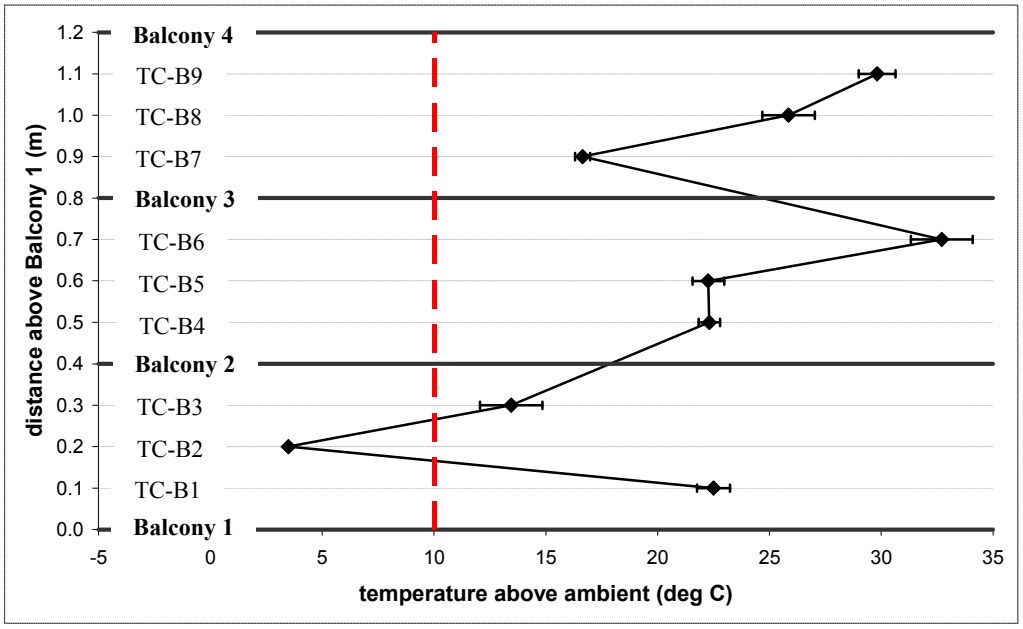
	✓✓ Balcony 3 ✓ Balcony 2 ✘ Balcony 1

Figure C-32: Experiment 39

TEMPERATURE PROFILES ACROSS BALCONY EDGE

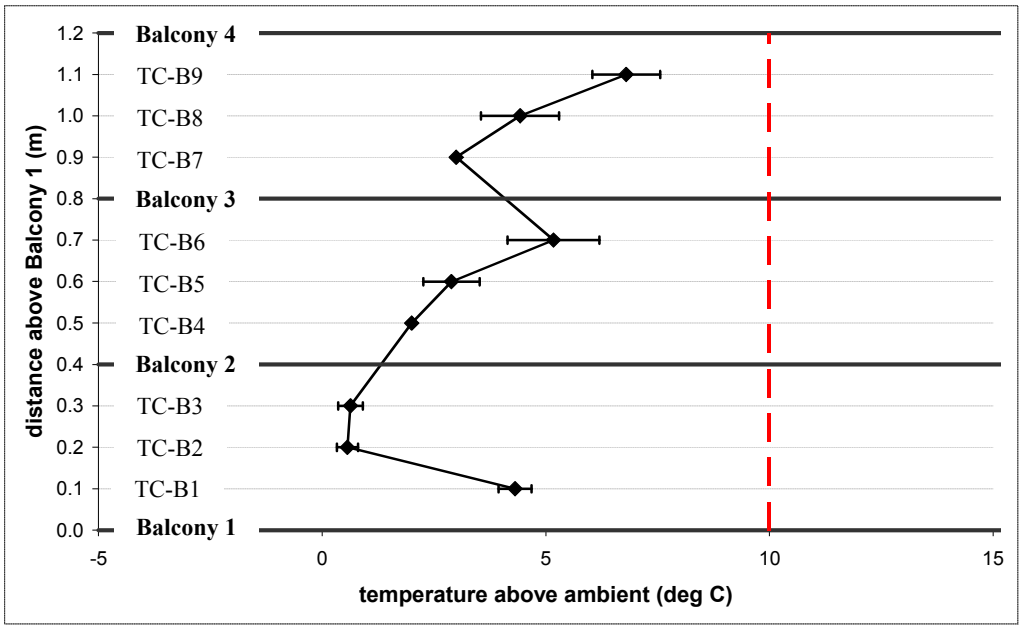
Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-33: Experiment 40

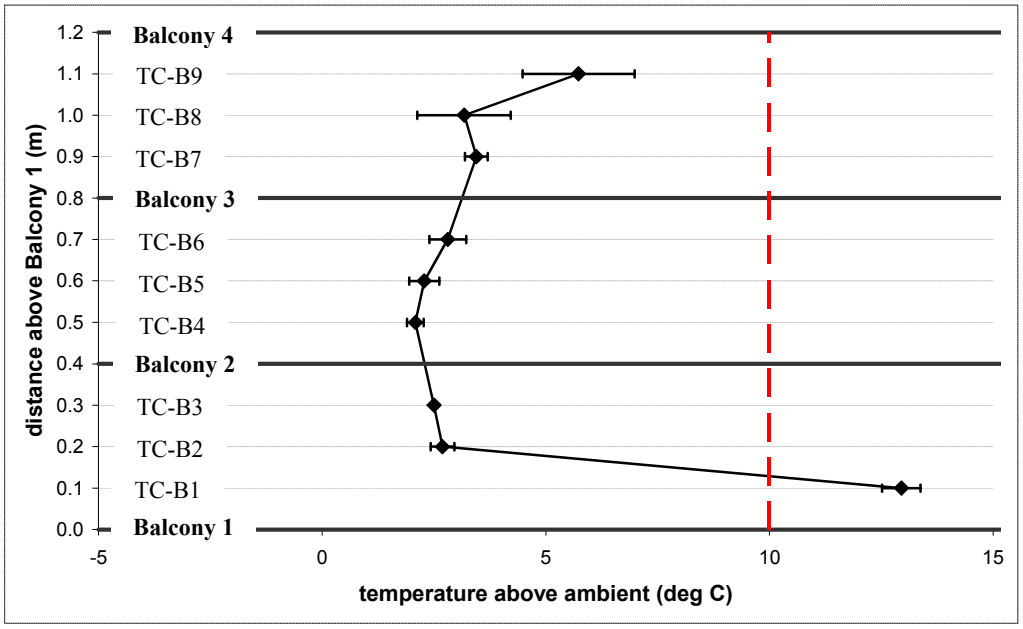
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-34: Experiment 41

TEMPERATURE PROFILES ACROSS BALCONY EDGE

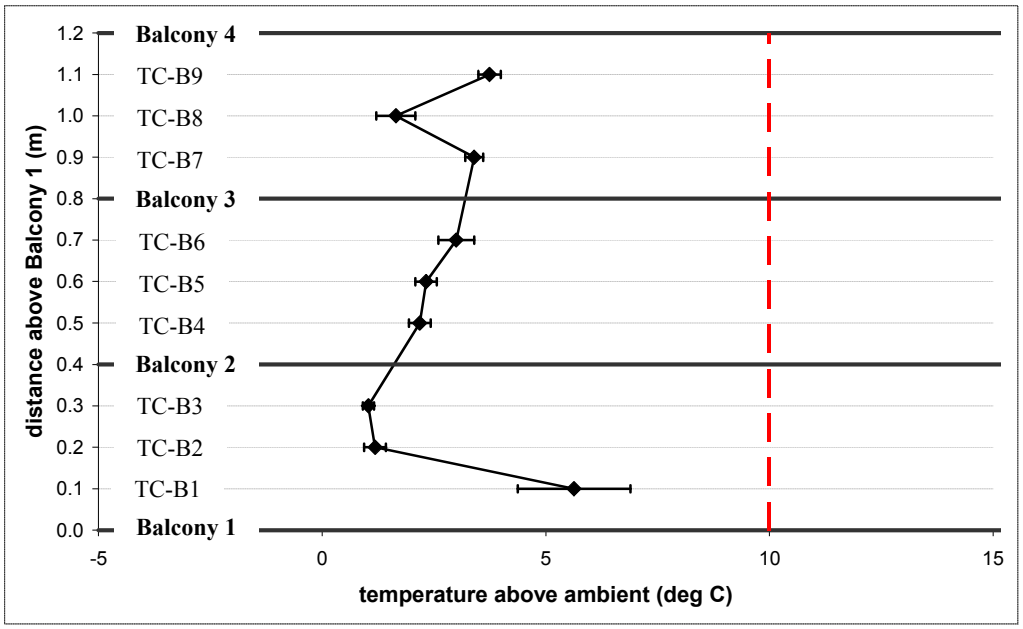
Temperature Profiles	Visual Observations
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-35: Experiment 43

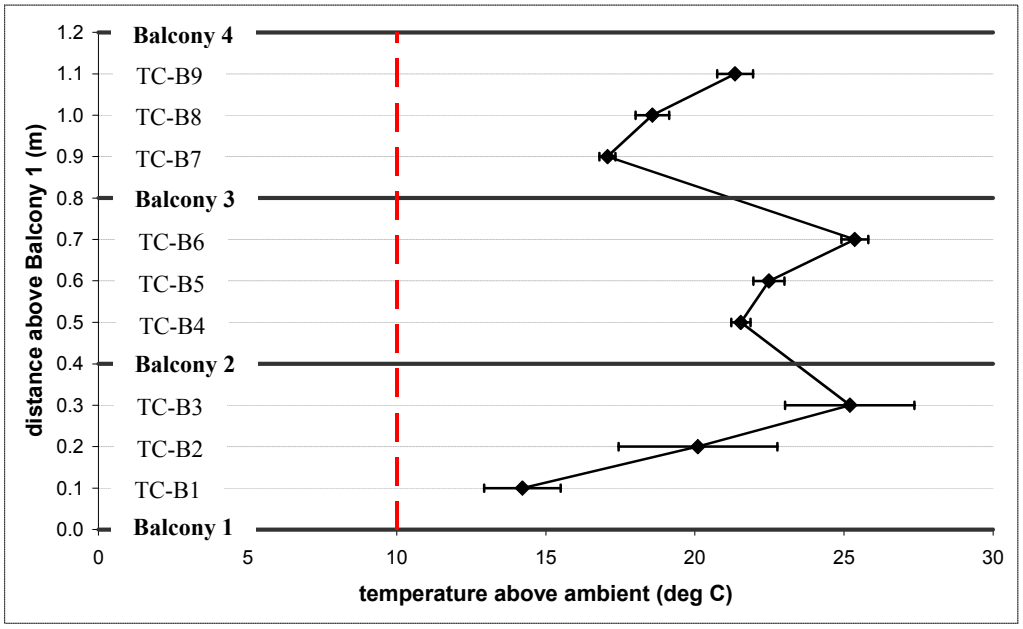
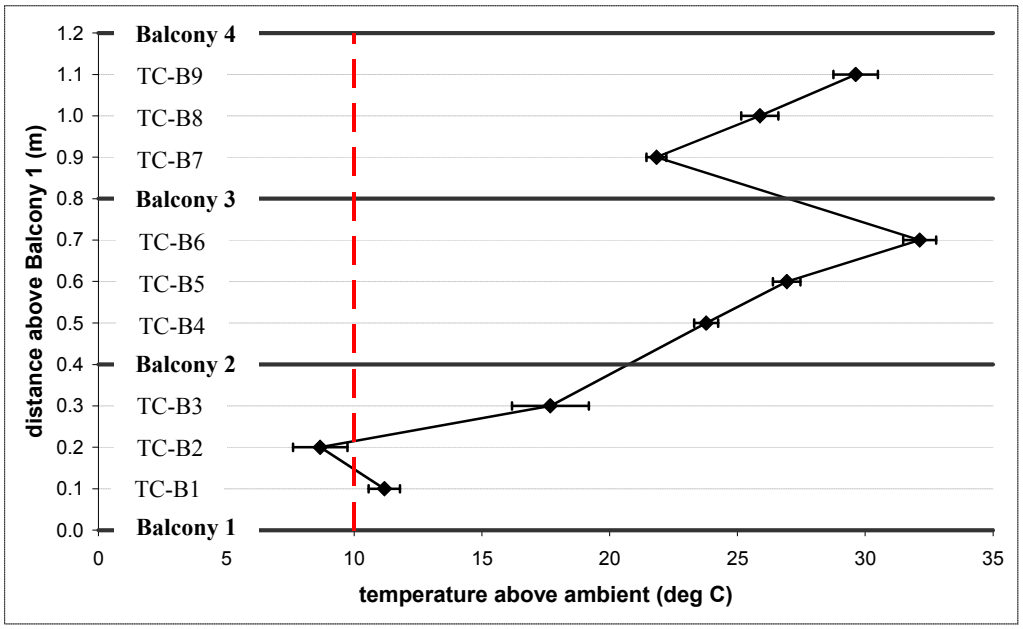
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1

Figure C-36: Experiment 46

TEMPERATURE PROFILES ACROSS BALCONY EDGE

Temperature Profiles	Visual Observations

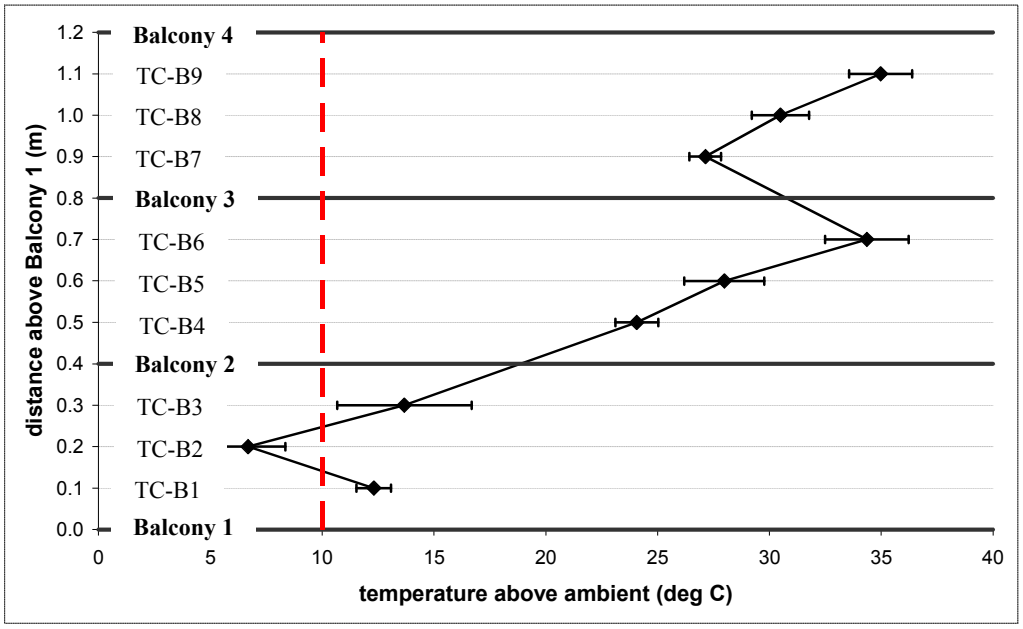


✓✓ Balcony 3

✓✓ Balcony 2

✓✓ Balcony 1

Figure C-37: Experiment 47



✓✓ Balcony 3

✓✓ Balcony 2

✓✓ Balcony 1

Figure C-38: Experiment 48

TEMPERATURE PROFILES ACROSS BALCONY EDGE

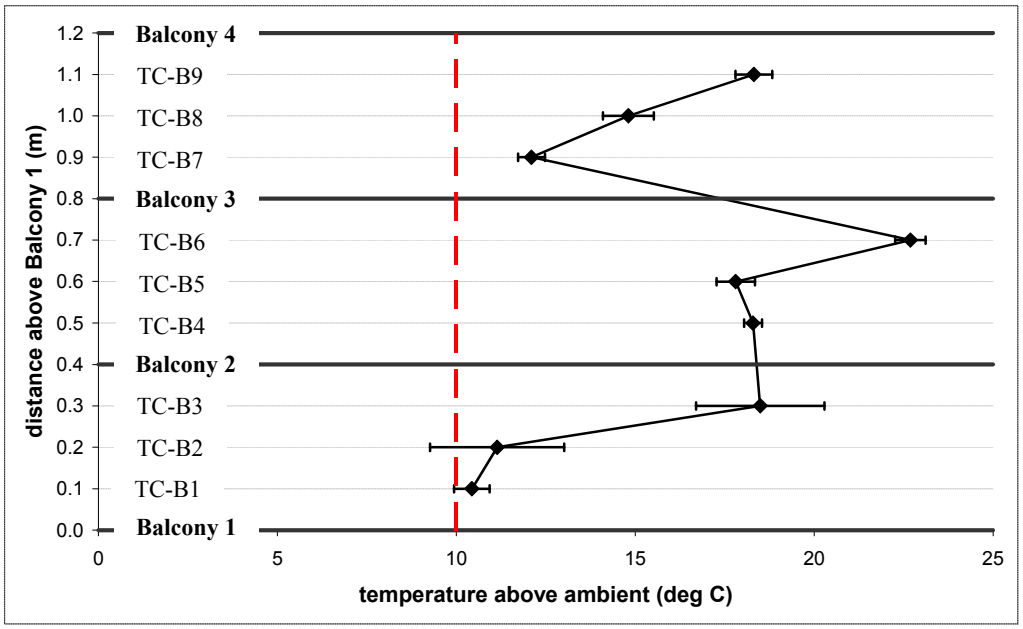
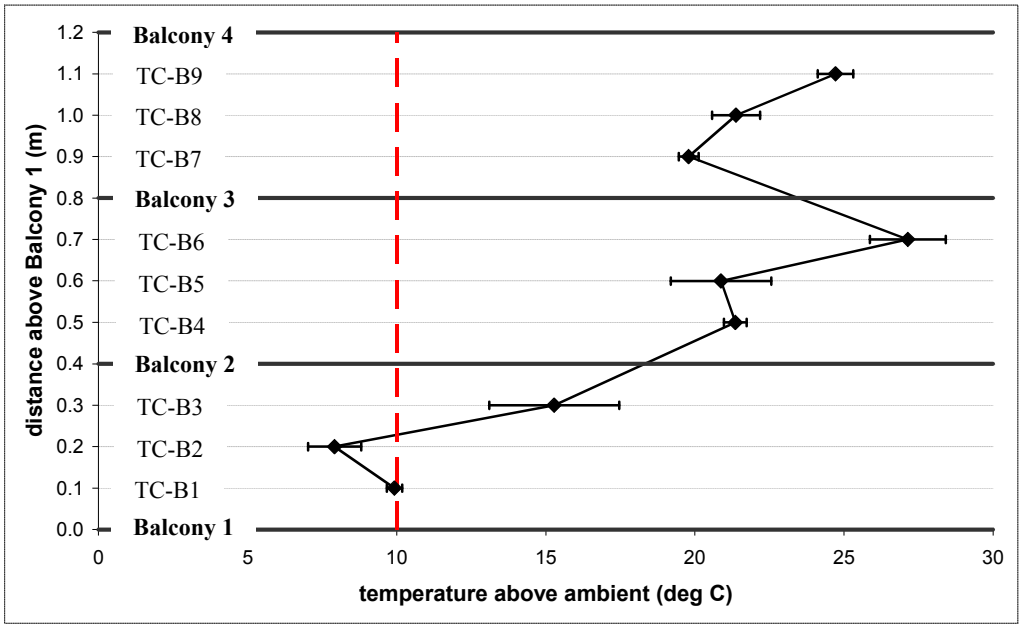
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1

Figure C-39: Experiment 49



✓✓ Balcony 3
✓✓ Balcony 2
✓✓ Balcony 1

Figure C-40: Experiment 50

TEMPERATURE PROFILES ACROSS BALCONY EDGE

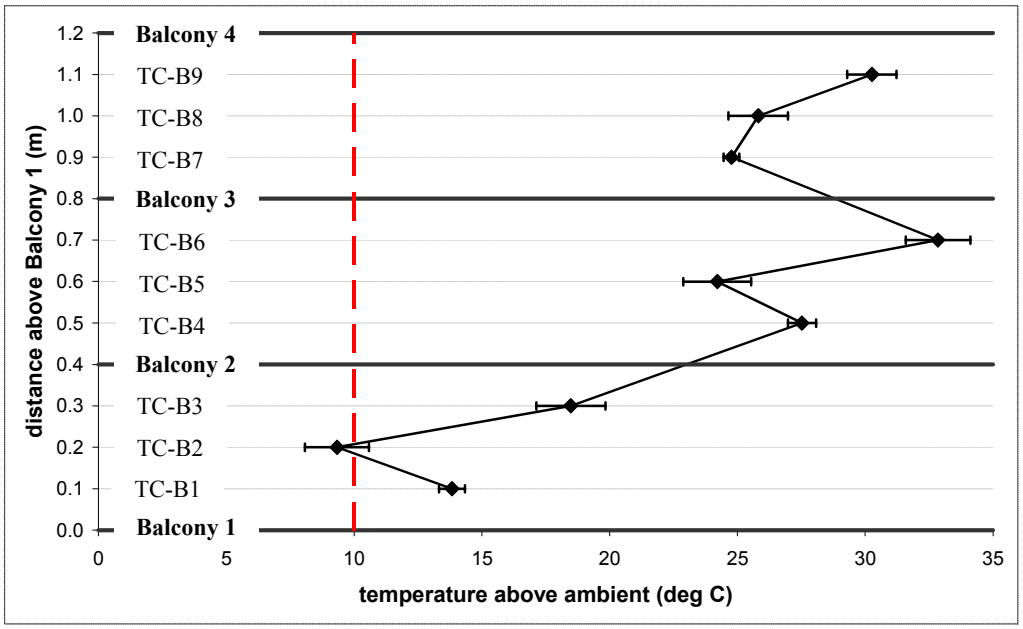
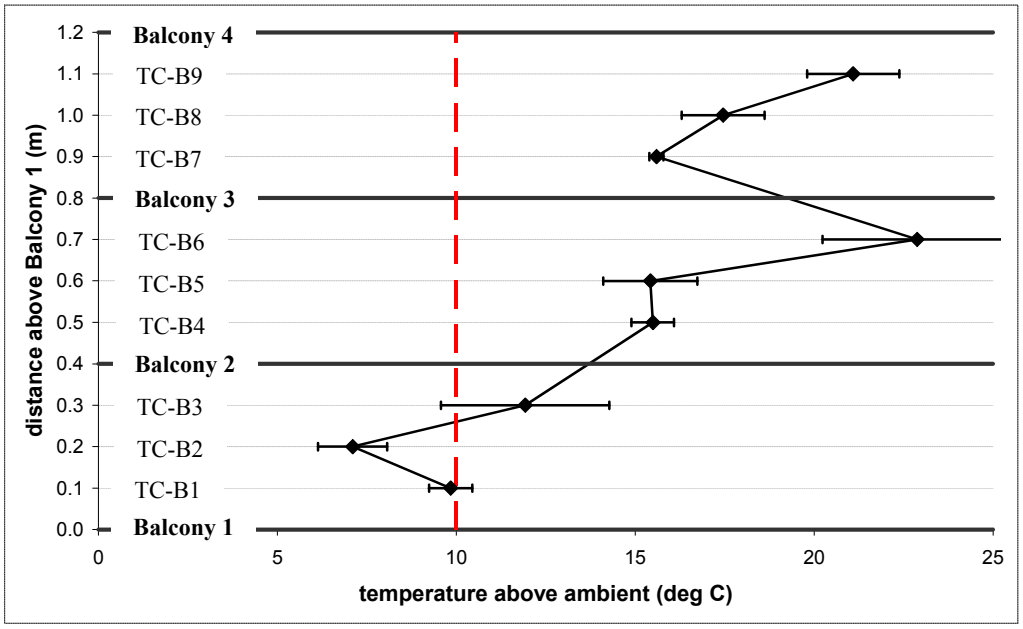
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure C-41: Experiment 51



✓✓ Balcony 3
✓✓ Balcony 2
✓ Balcony 1

Figure C-42: Experiment 52

TEMPERATURE PROFILES ACROSS BALCONY EDGE

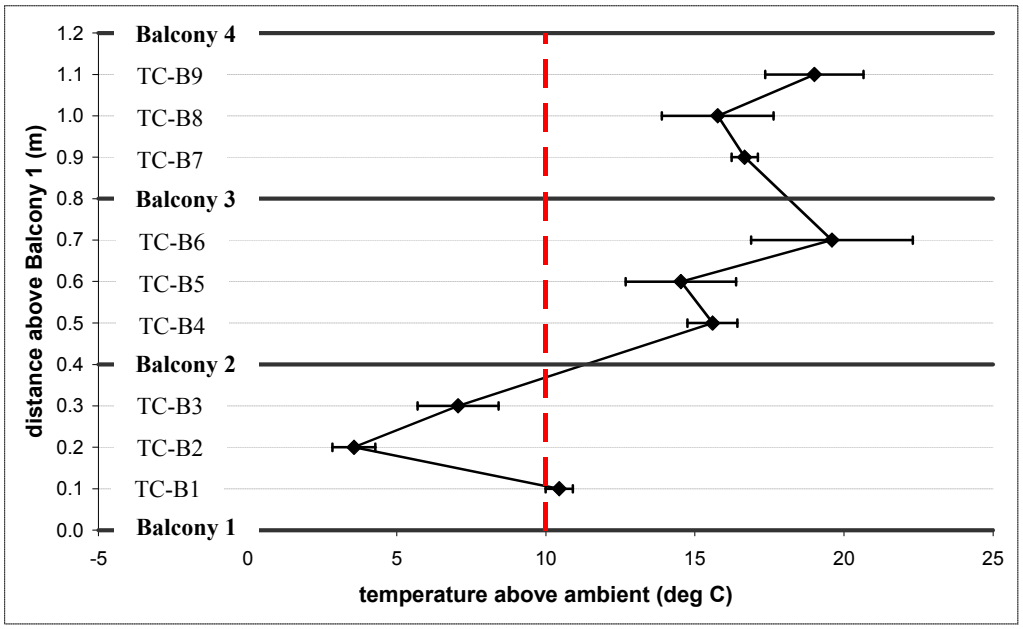
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓ Balcony 2 ✓ Balcony 1

Figure C-43: Experiment 53

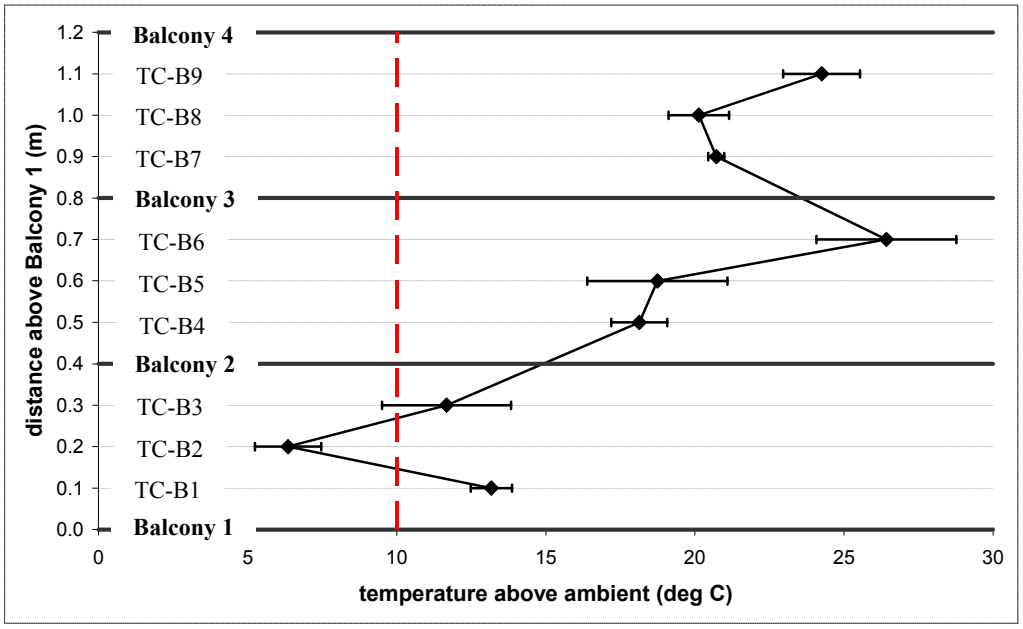
	✓✓ Balcony 3 ✓ Balcony 2 ✘ Balcony 1

Figure C-44: Experiment 54

TEMPERATURE PROFILES ACROSS BALCONY EDGE

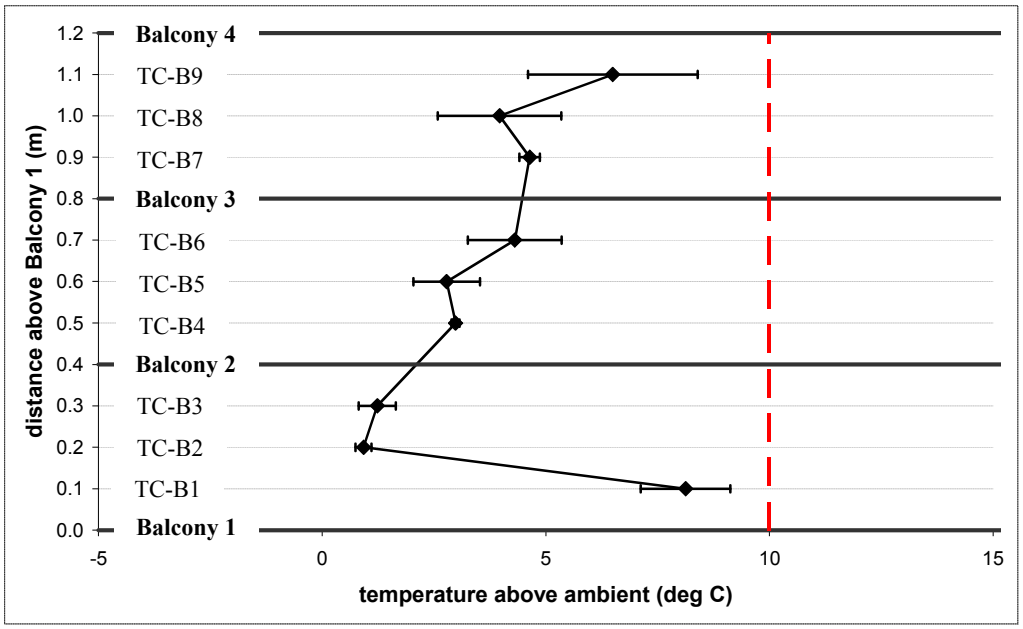
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-45: Experiment 55

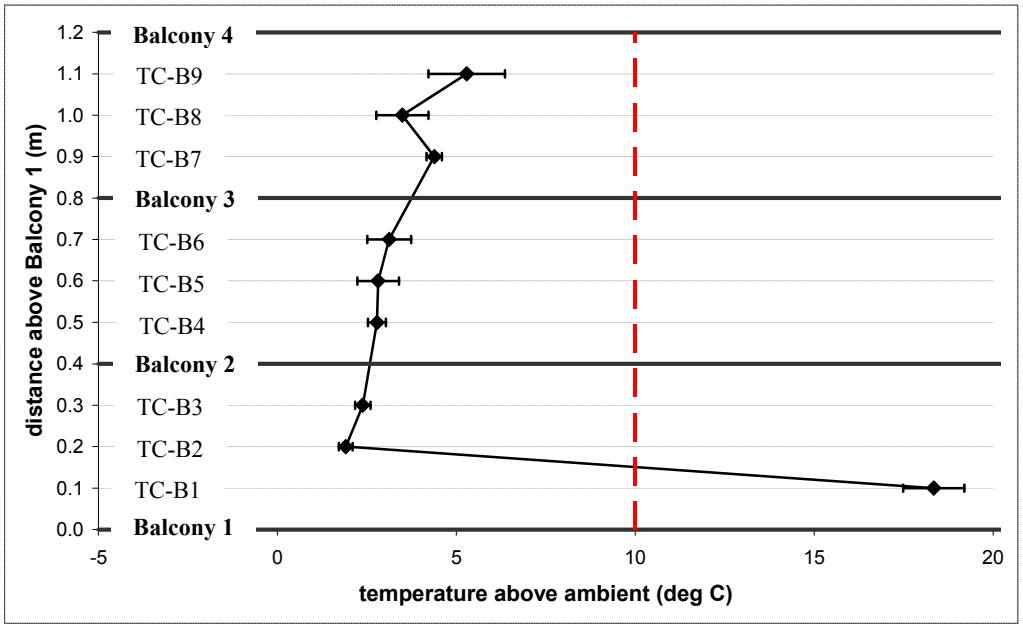
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-46: Experiment 56

TEMPERATURE PROFILES ACROSS BALCONY EDGE

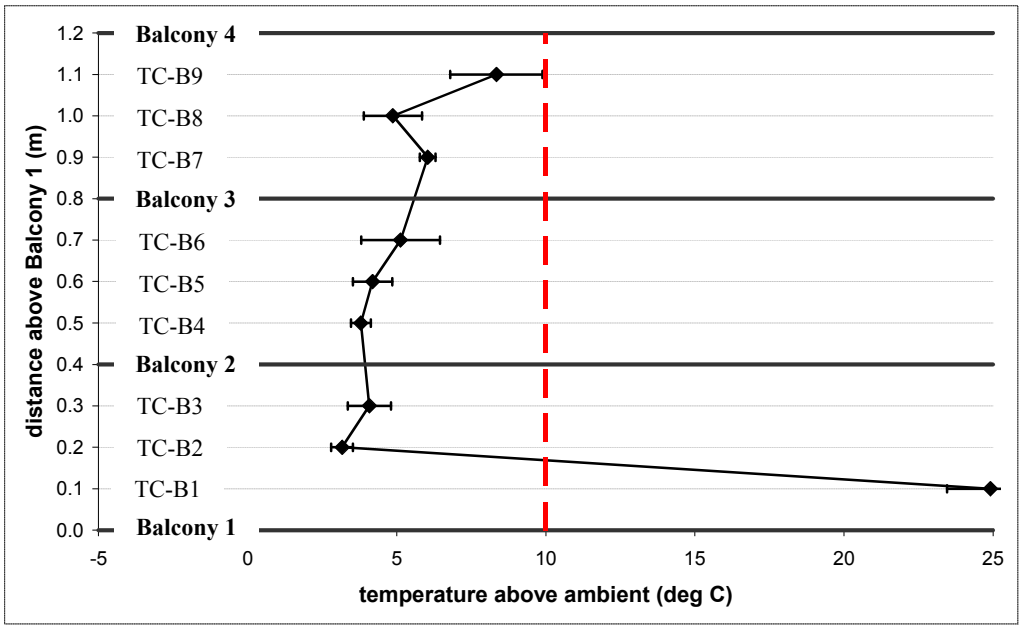
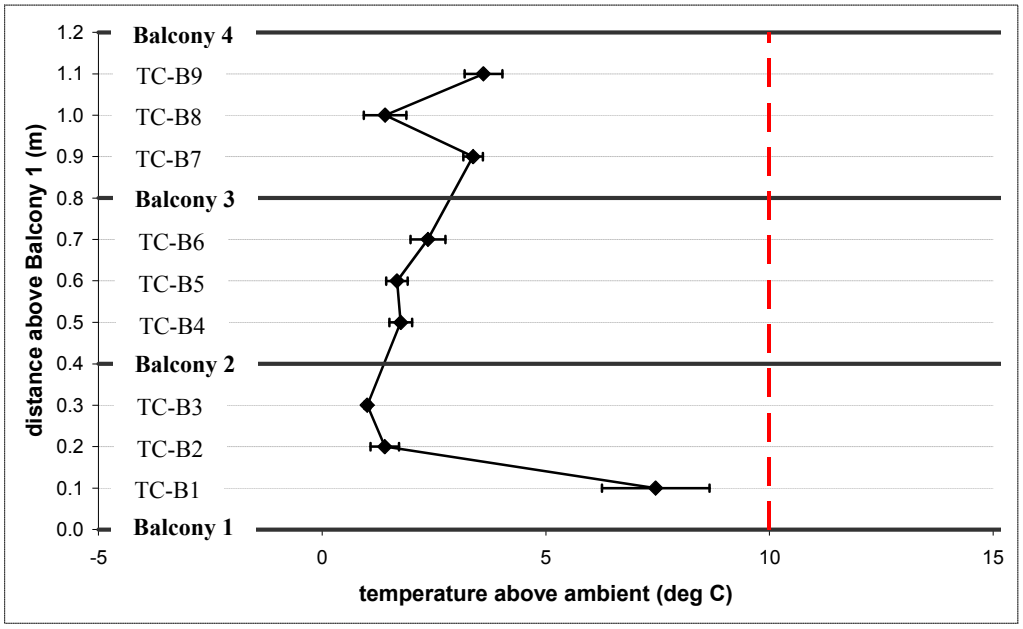
Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-47: Experiment 57



✓ Balcony 3
✗ Balcony 2
✗ Balcony 1

Figure C-48: Experiment 58

TEMPERATURE PROFILES ACROSS BALCONY EDGE

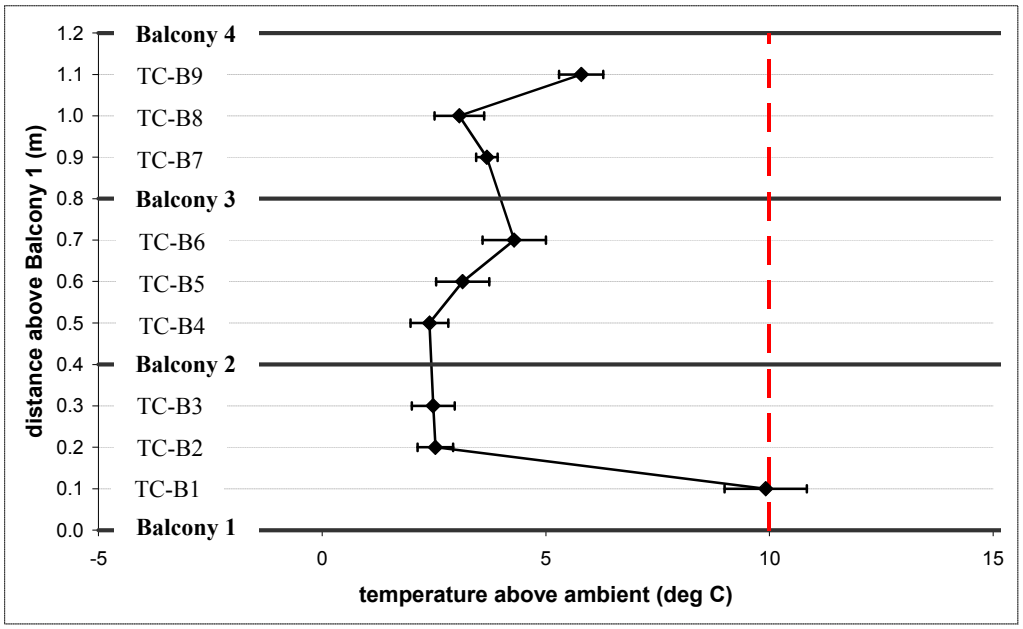
Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-49: Experiment 59

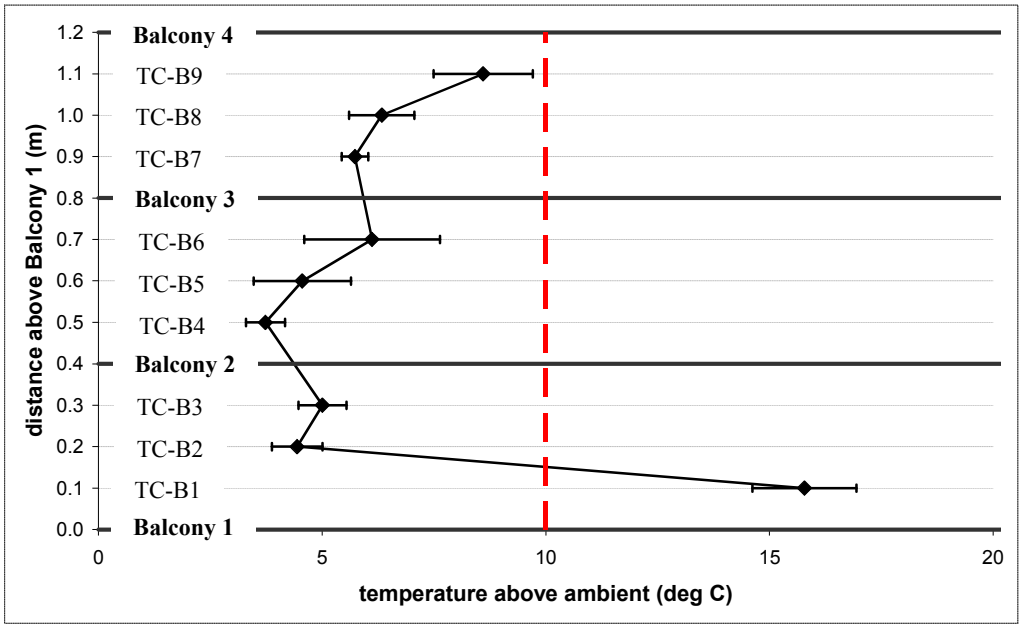
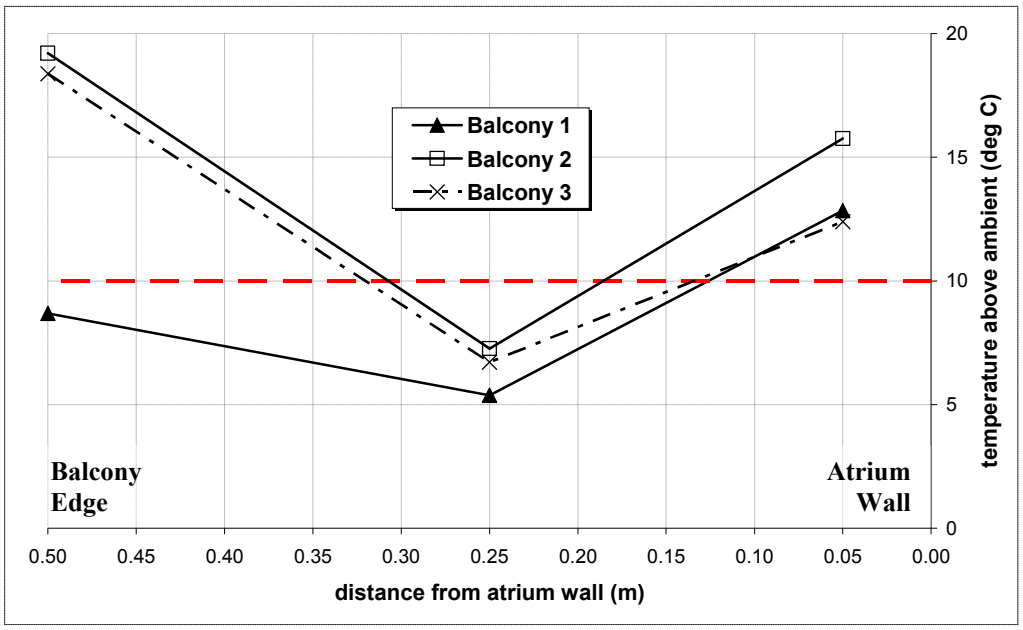
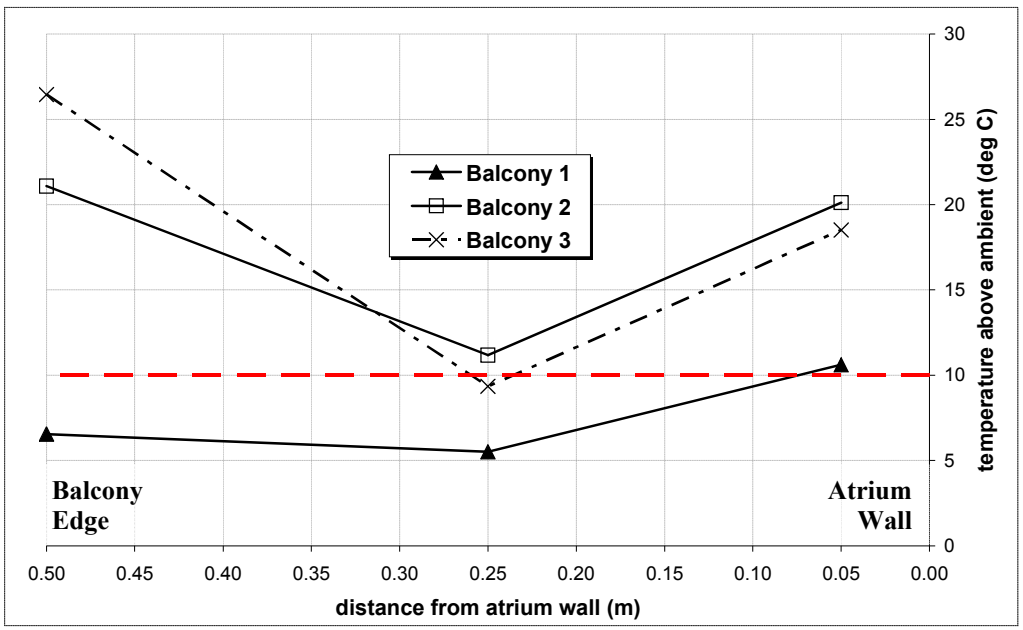
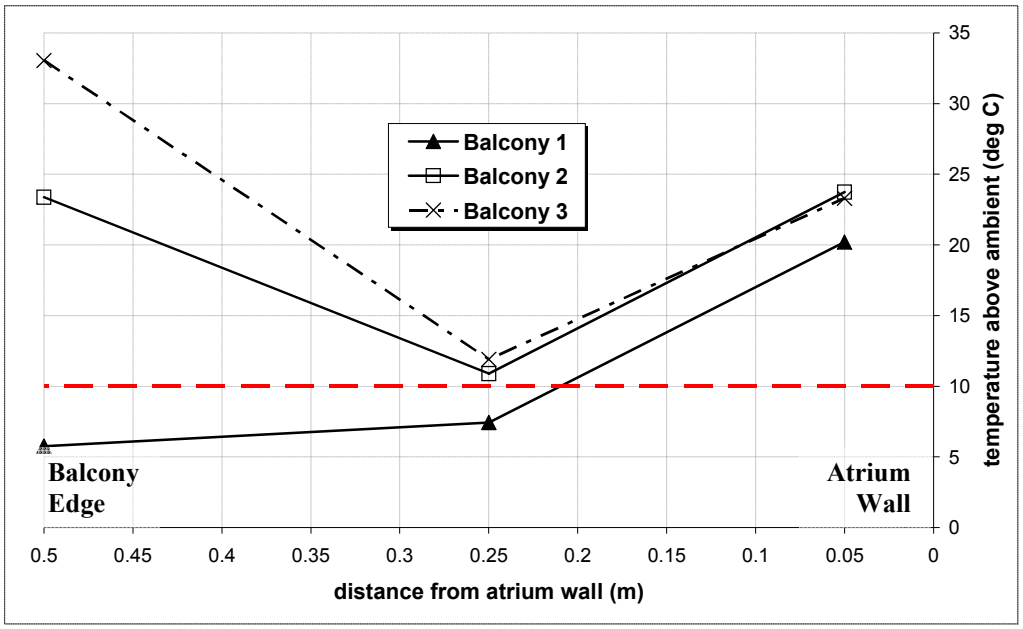
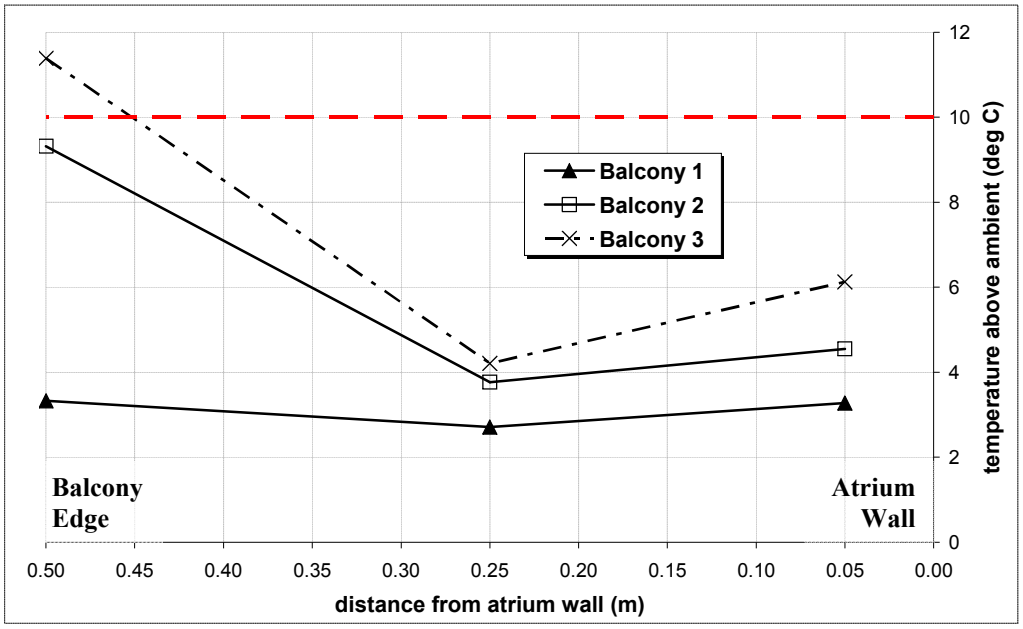
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure C-50: Experiment 60

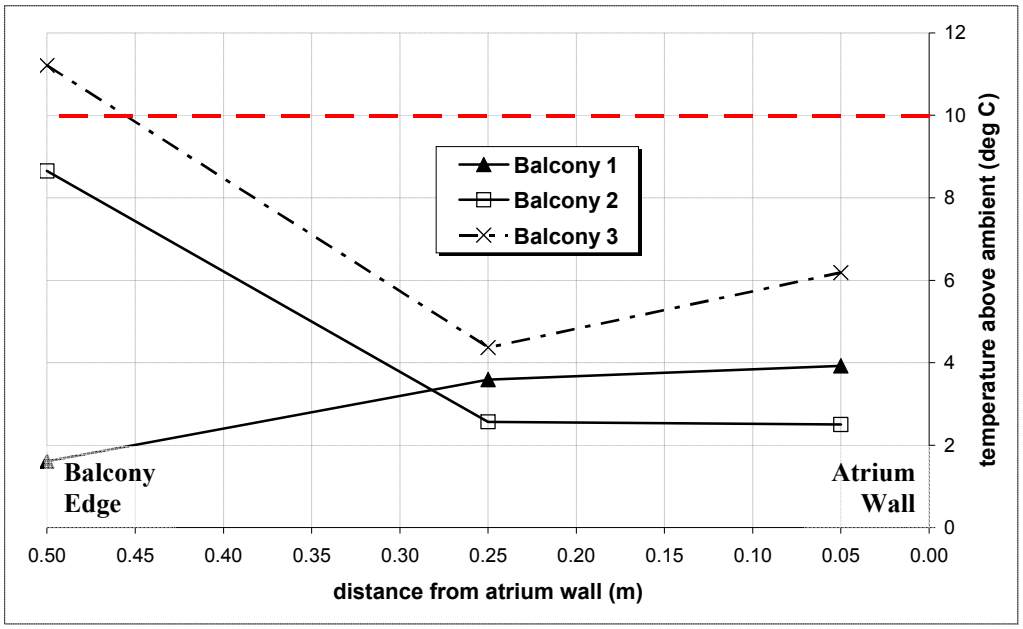
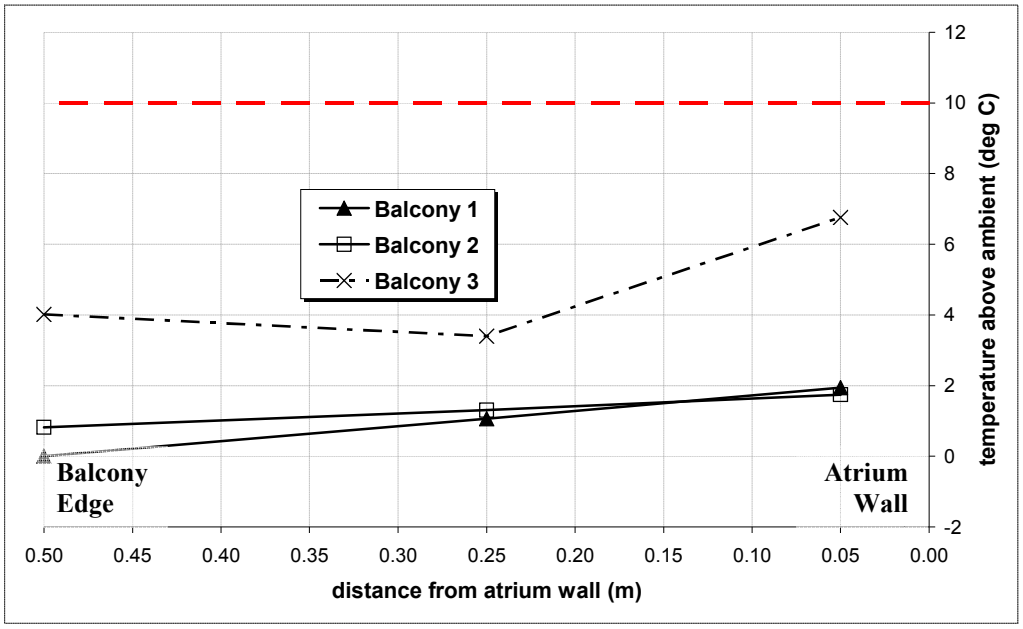
TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure D-1: Experiment 1	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure D-2: Experiment 2	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure D-3: Experiment 3	
	✓✓ Balcony 3 ✓ Balcony 2 ✘ Balcony 1
Figure D-4: Experiment 4	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓ Balcony 2 ✗ Balcony 1
Figure D-5: Experiment 5	
	✓✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-6: Experiment 6	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

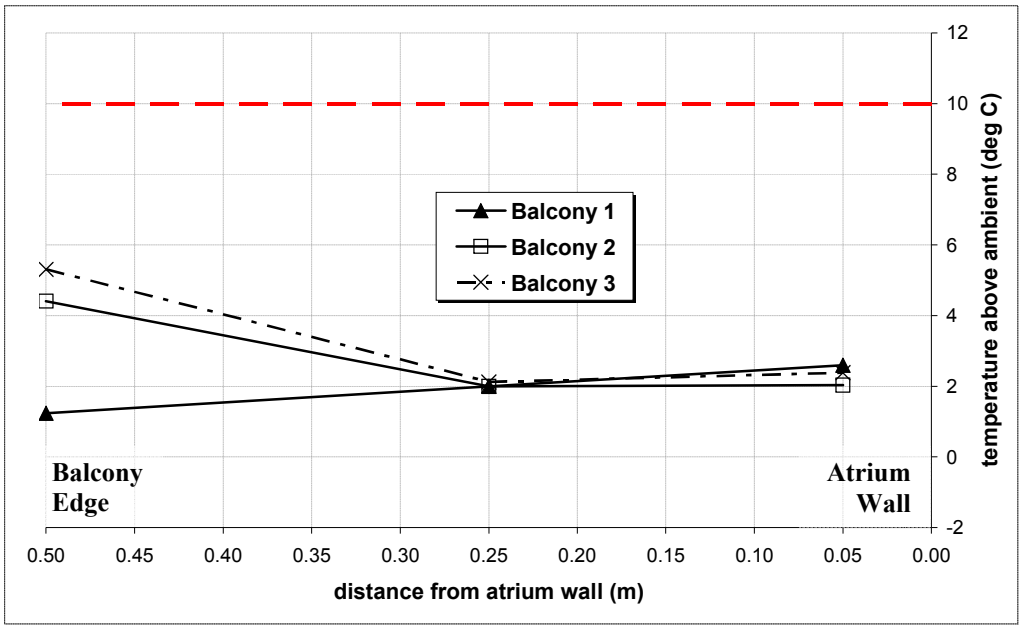
Temperature Profiles	Visual Observations
	

Figure D-7: **Experiment 7**

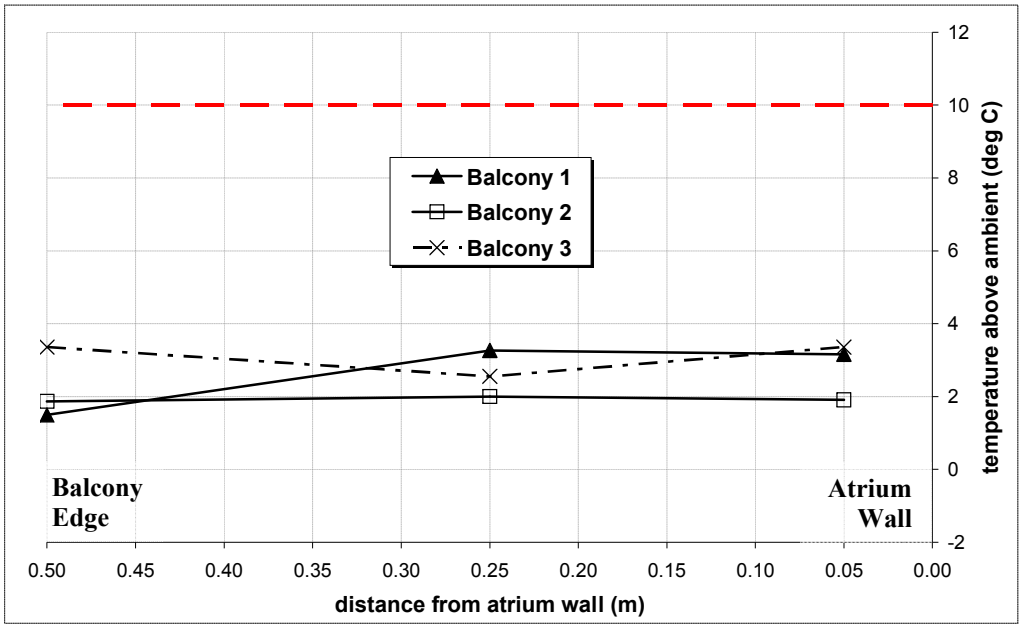


Figure D-8: **Experiment 8**

TEMPERATURE PROFILES ALONG BALCONY BREADTH

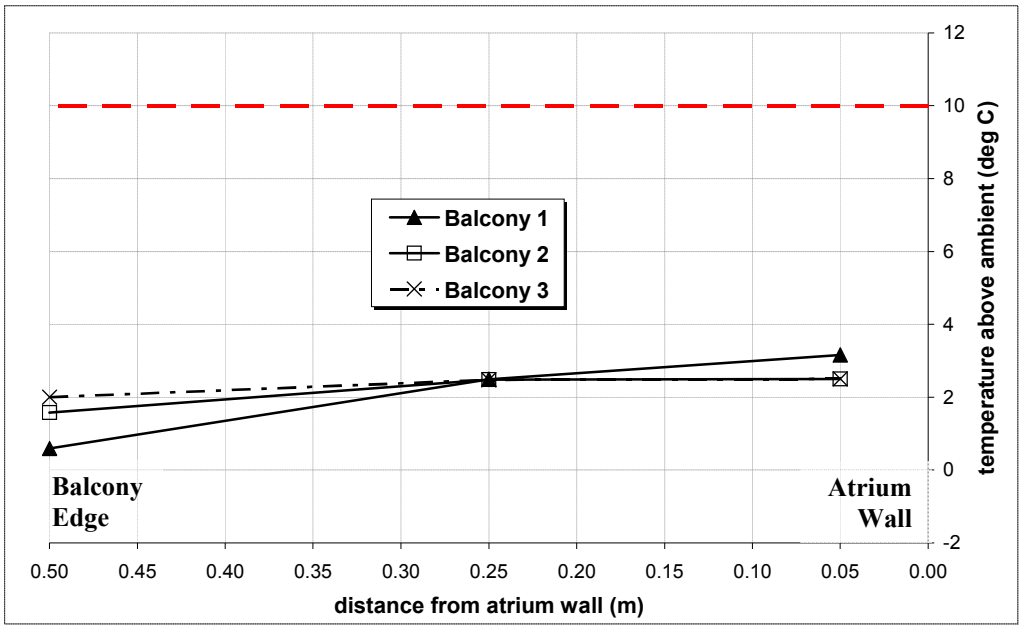
Temperature Profiles	Visual Observations
	

Figure D-9: Experiment 10

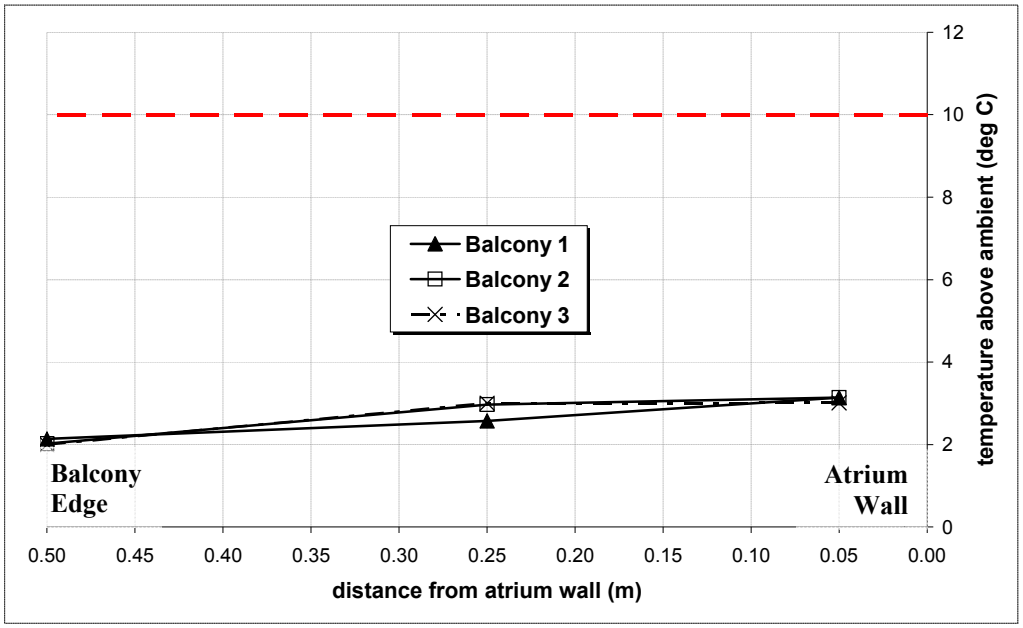


Figure D-10: Experiment 13

TEMPERATURE PROFILES ALONG BALCONY BREADTH

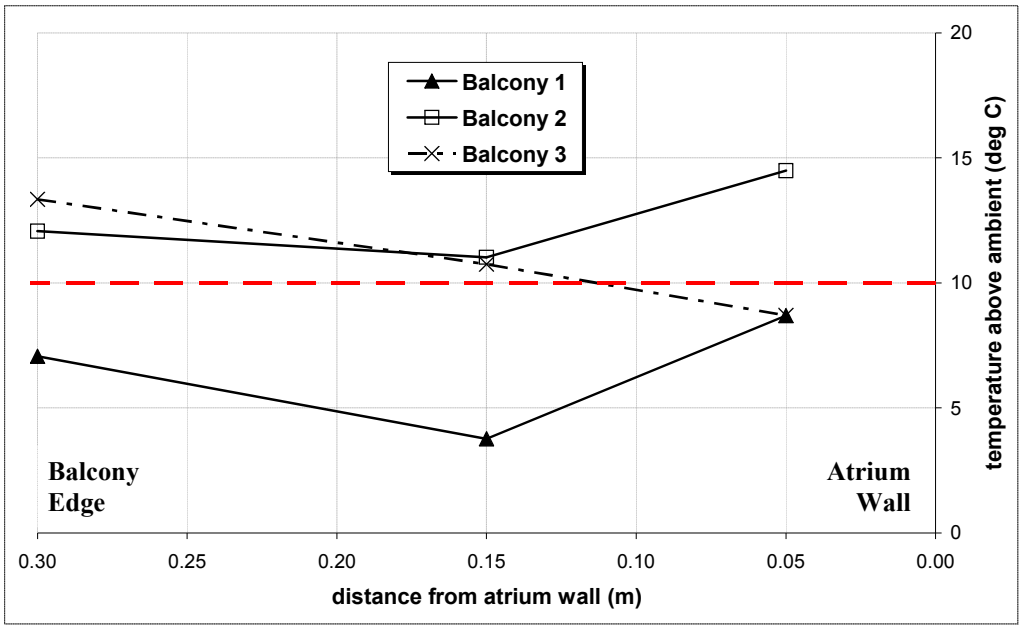
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure D-11: Experiment 16

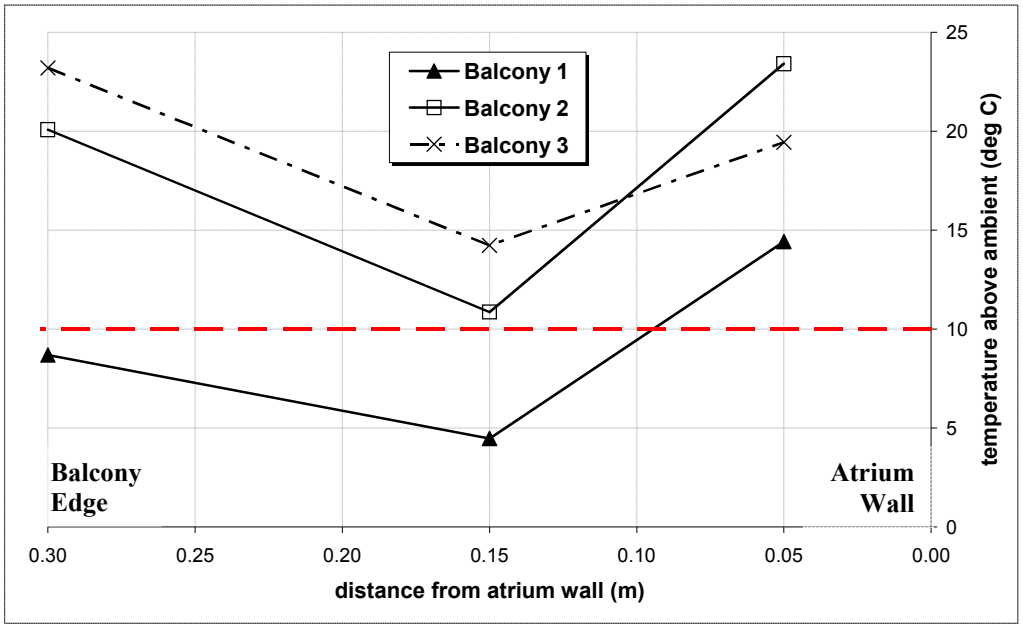
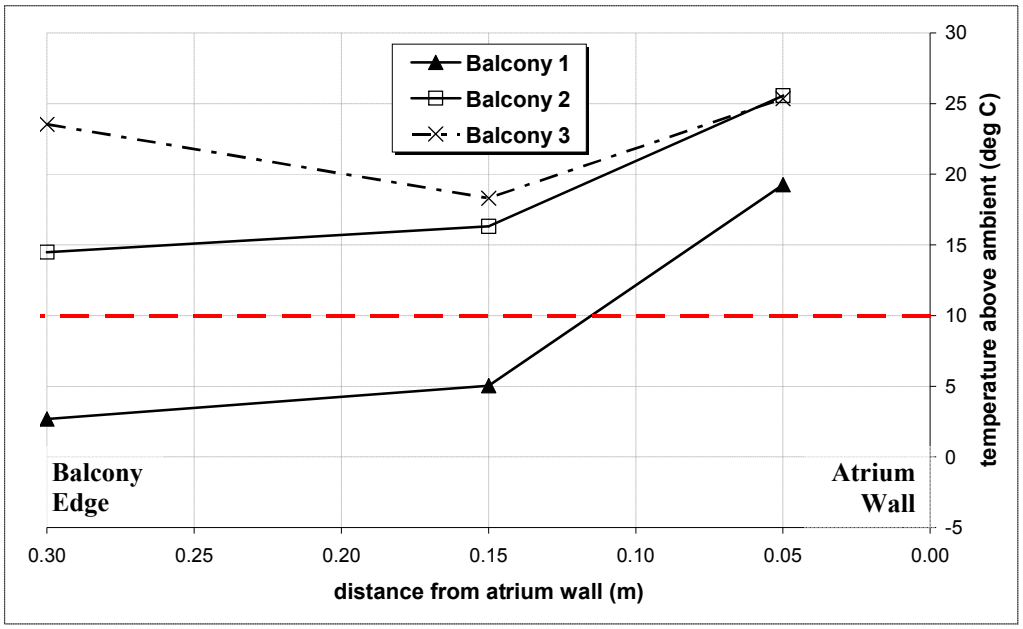
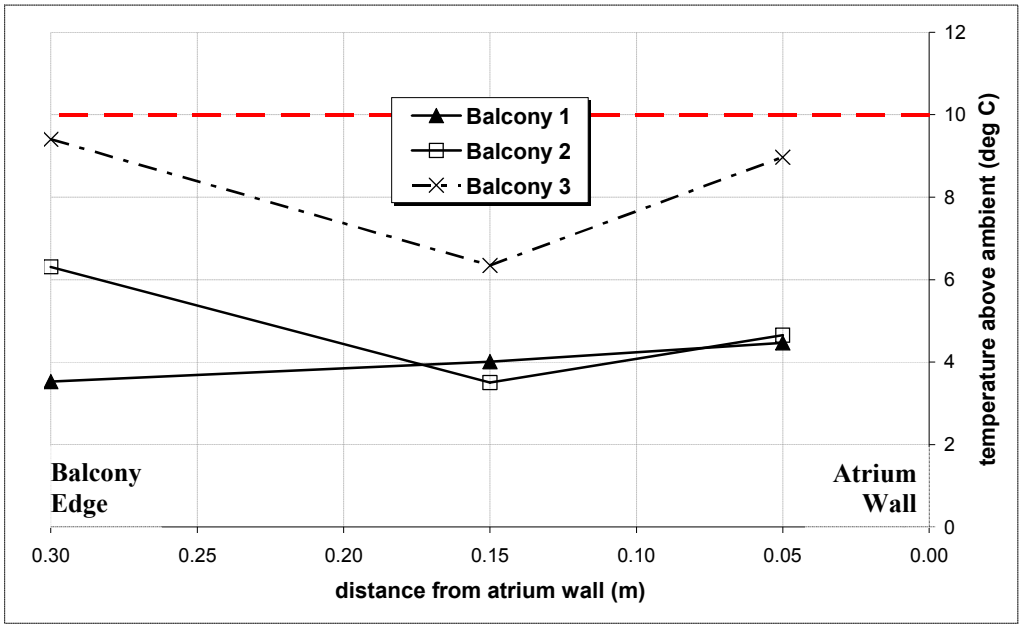


Figure D-12: Experiment 17

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure D-13: Experiment 18	
	✓✓ Balcony 3 ✓ Balcony 2 ✓ Balcony 1
Figure D-14: Experiment 19	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations

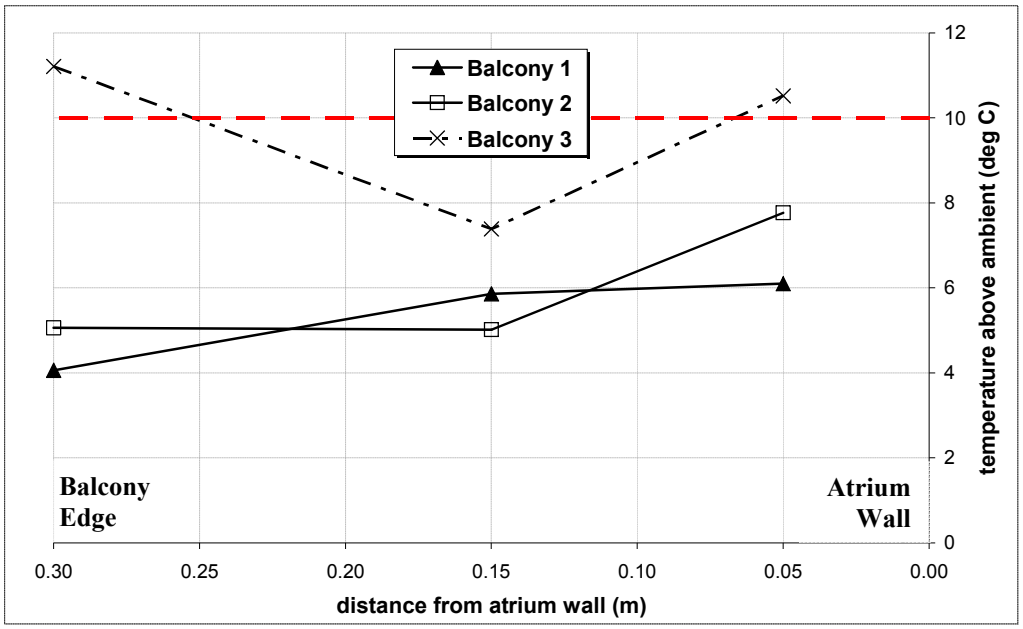


Figure D-15: Experiment 20

✓✓ Balcony 3

✓✓ Balcony 2

✓ Balcony 1

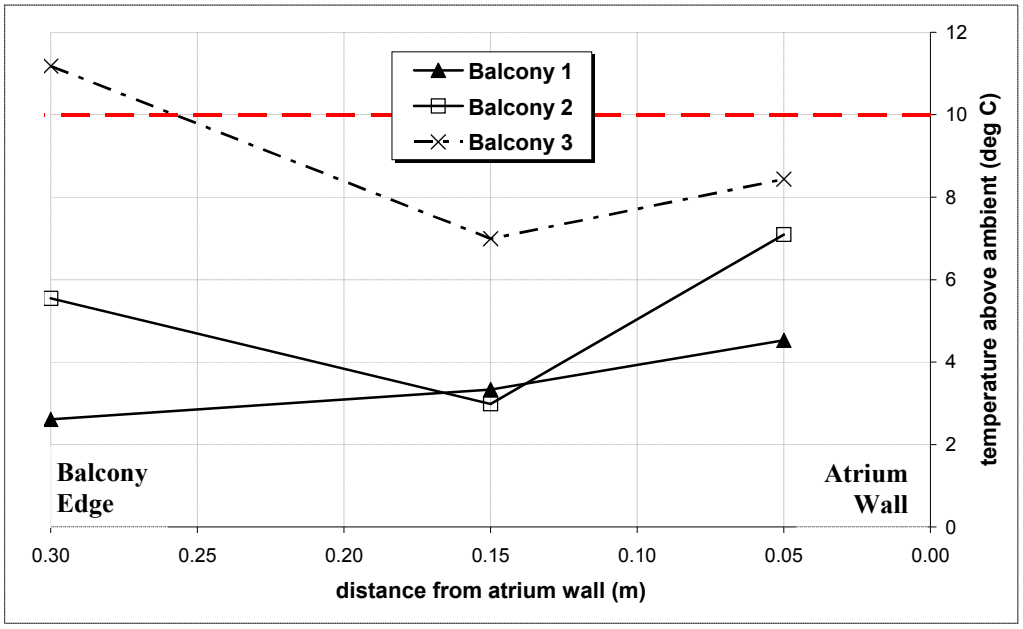


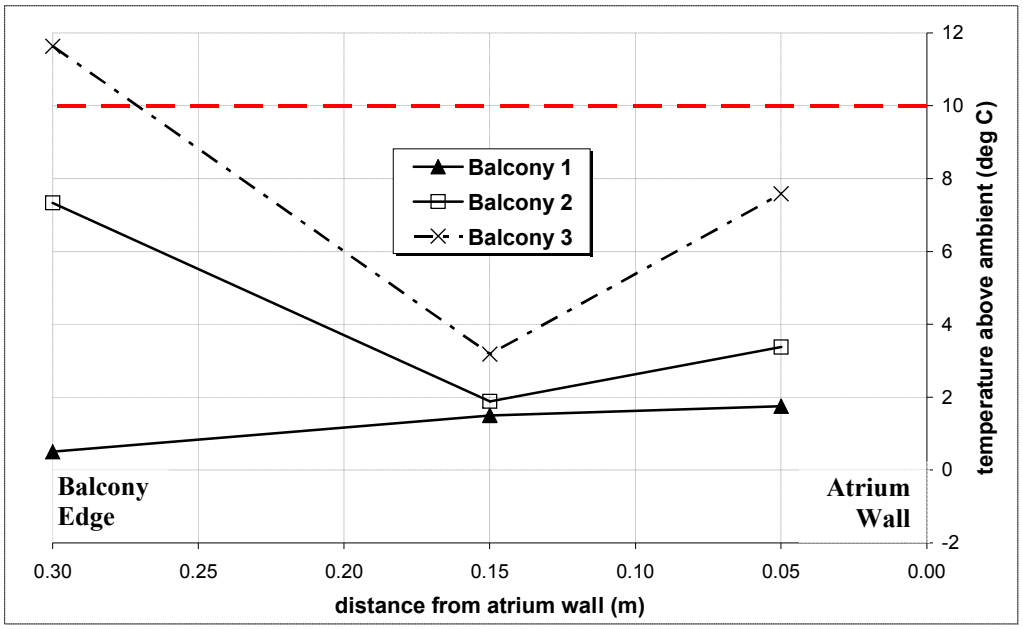
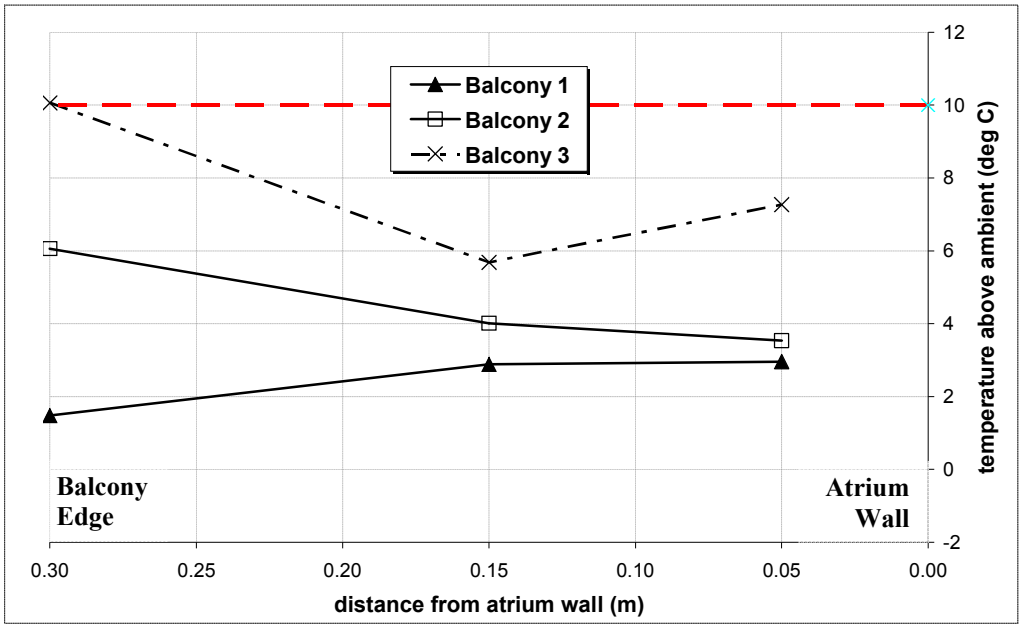
Figure D-16: Experiment 21

✓✓ Balcony 3

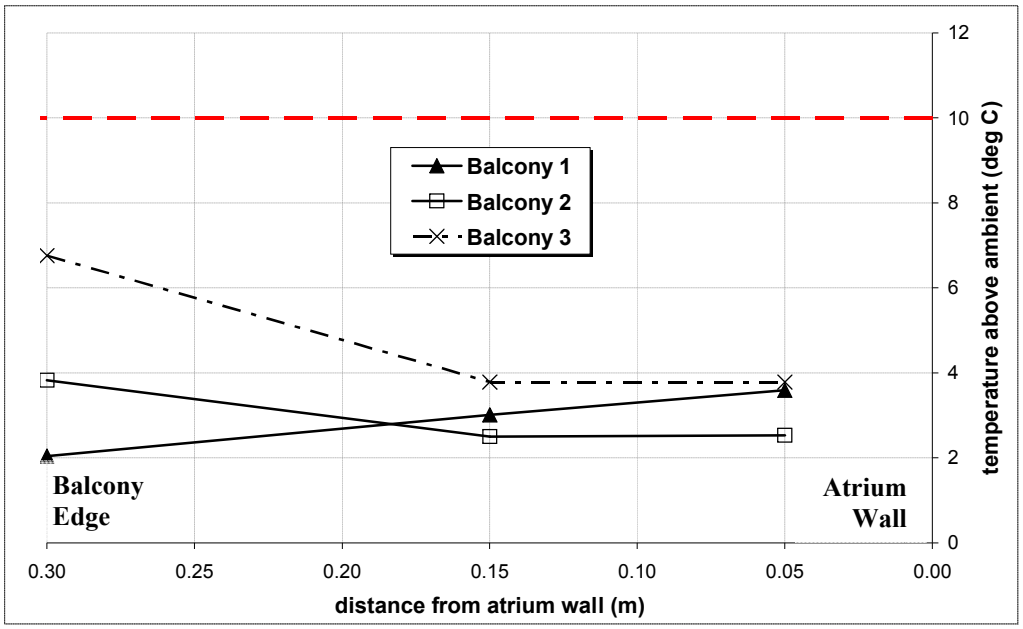
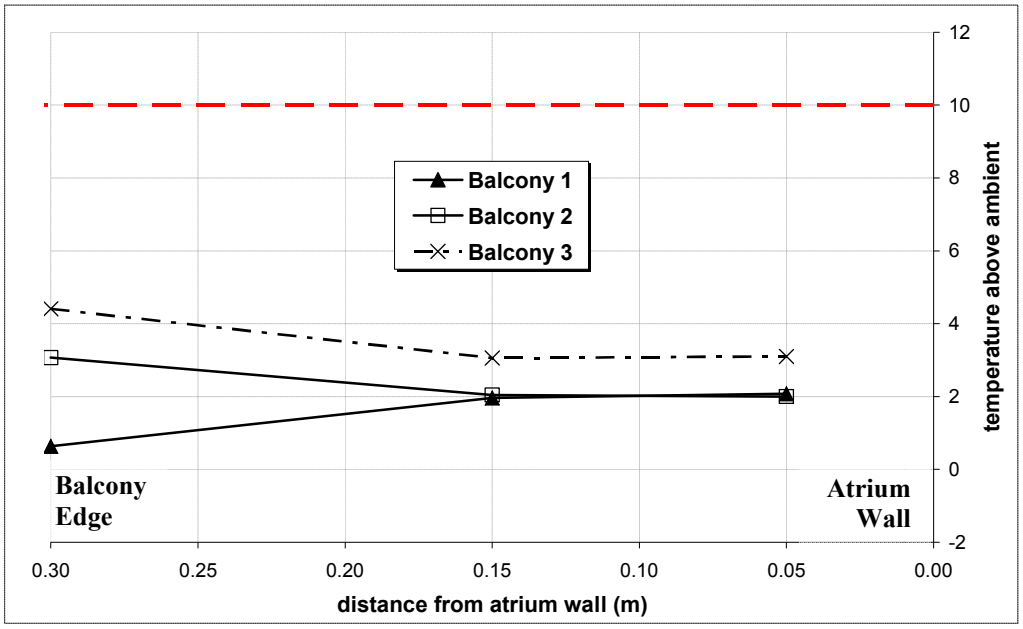
✓ Balcony 2

✘ Balcony 1

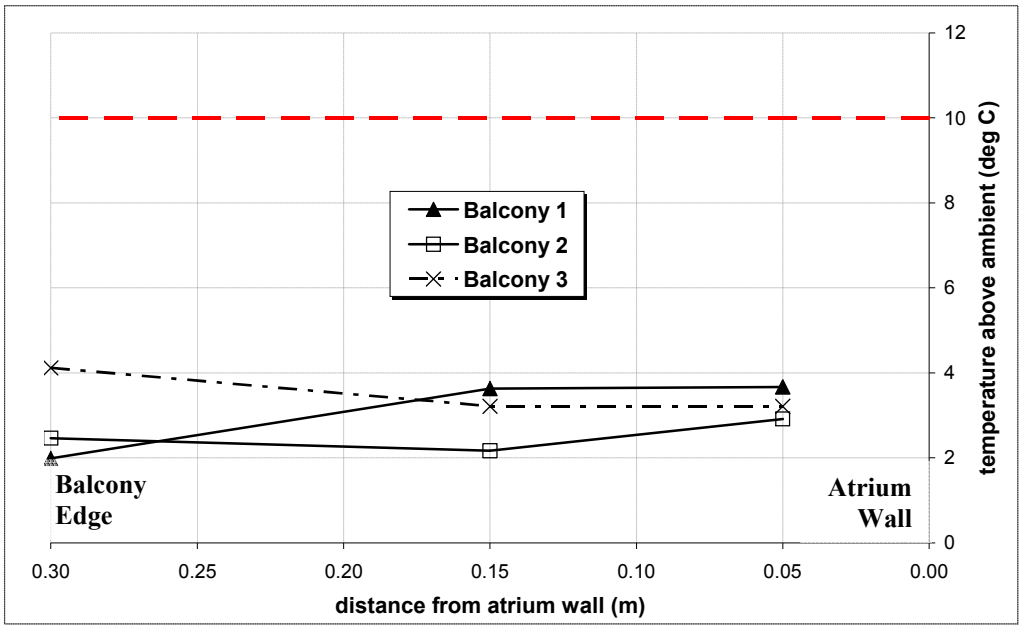
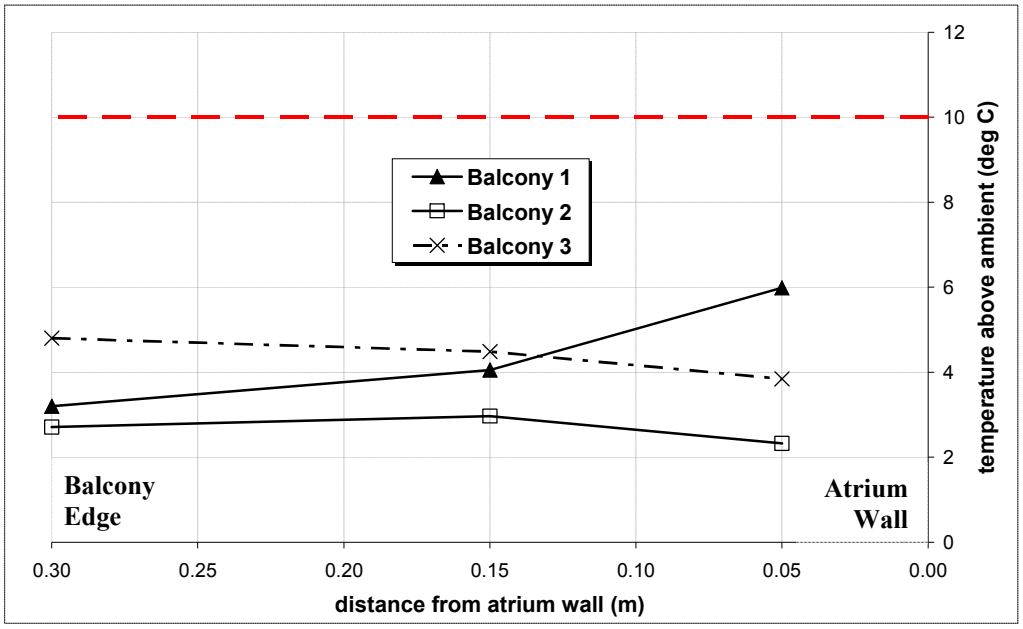
TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓ Balcony 2 ✗ Balcony 1
Figure D-17: Experiment 22	
	✓✓ Balcony 3 ✓ Balcony 2 ✗ Balcony 1
Figure D-18: Experiment 23	

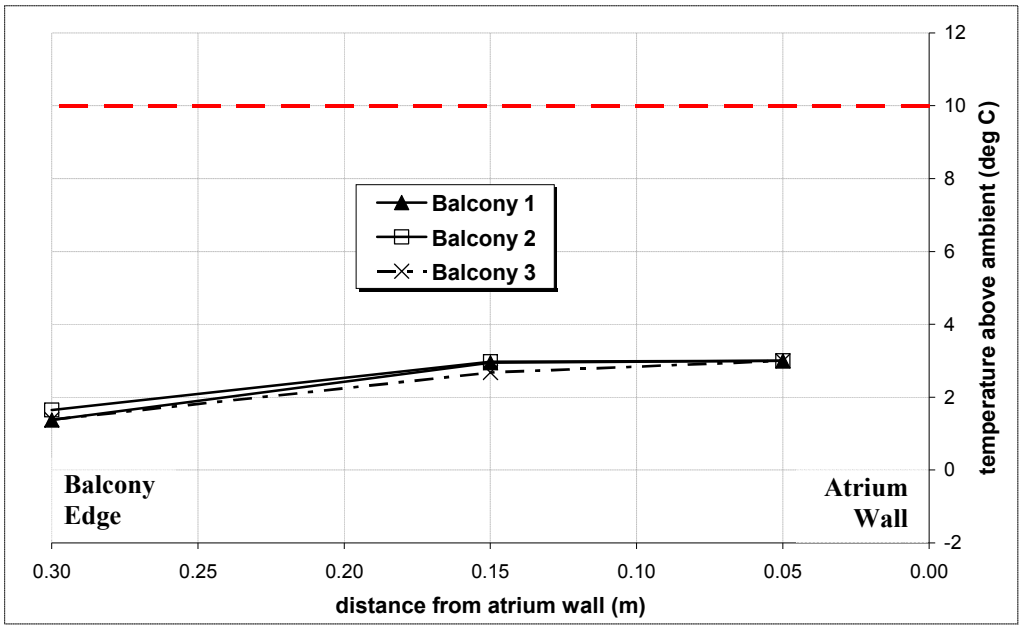
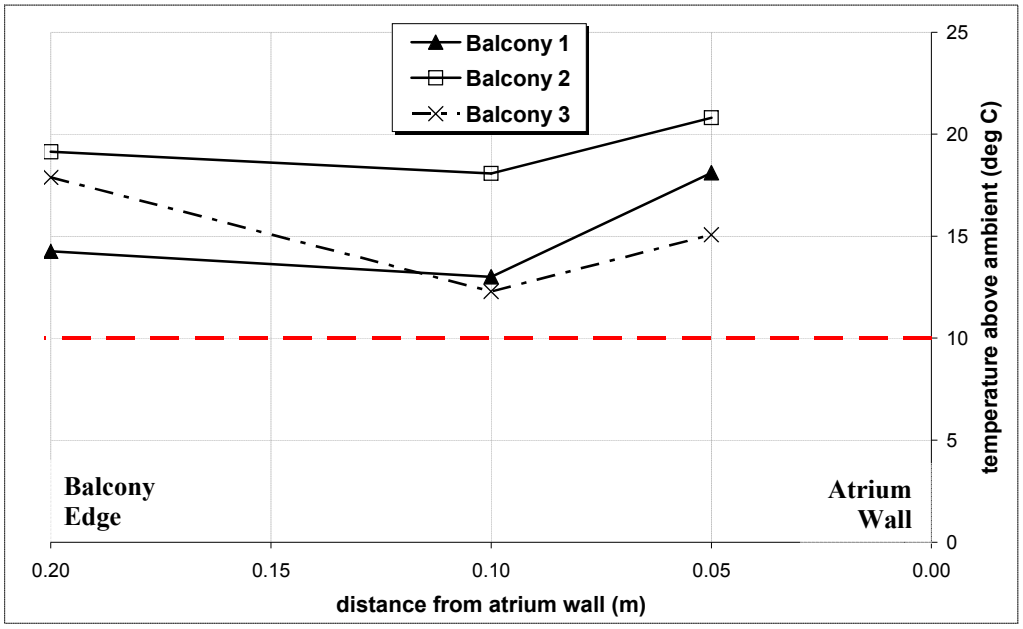
TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-19: Experiment 24	
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-20: Experiment 25	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-21: Experiment 26	
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-22: Experiment 27	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-23: Experiment 28	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1
Figure D-24: Experiment 31	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

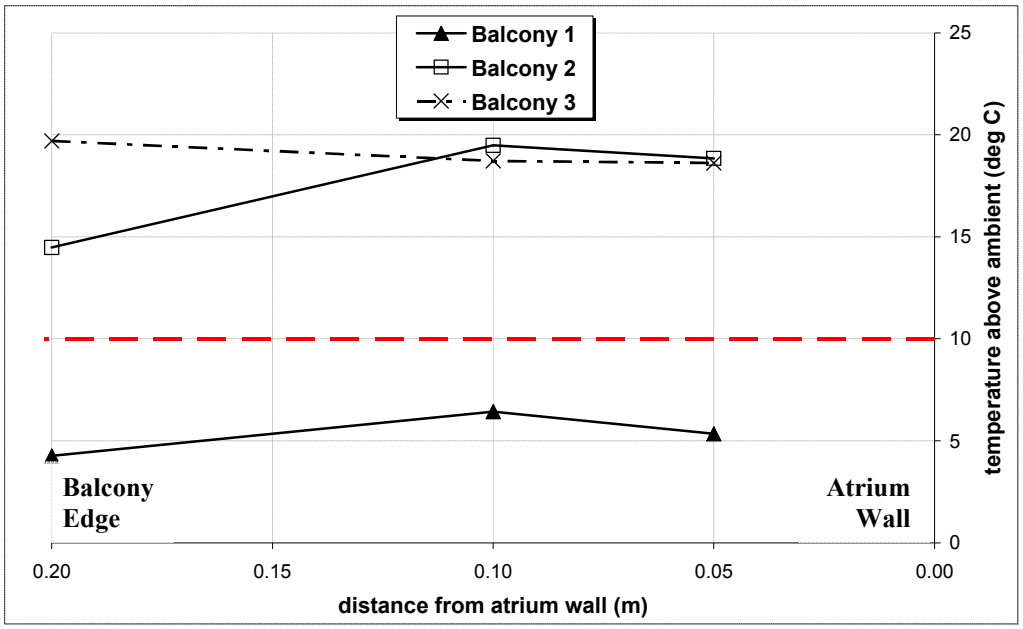
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1

Figure D-25: Experiment 32

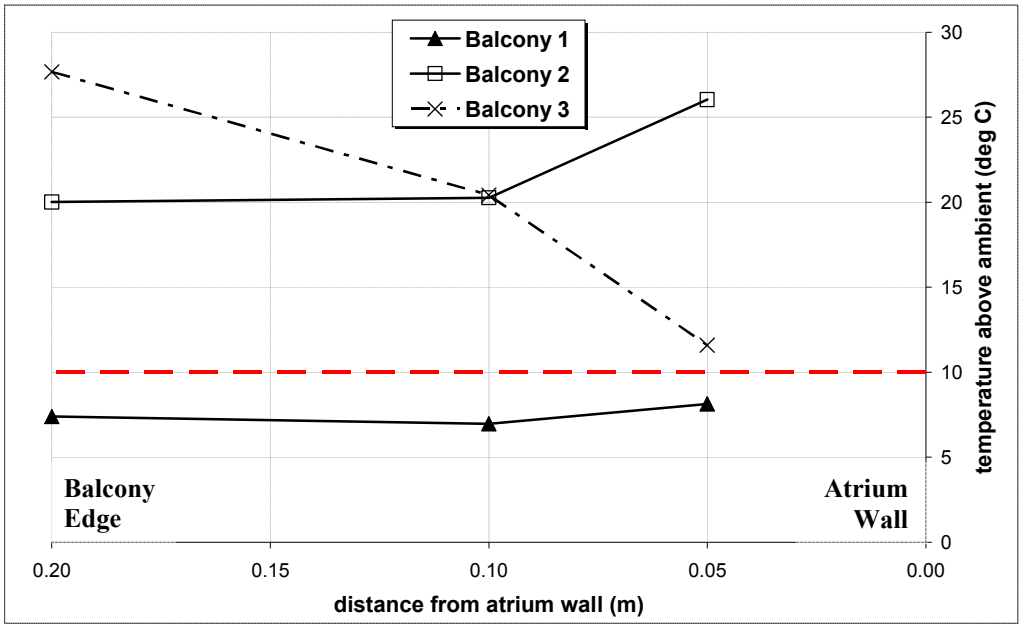
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1

Figure D-26: Experiment 33

TEMPERATURE PROFILES ALONG BALCONY BREADTH

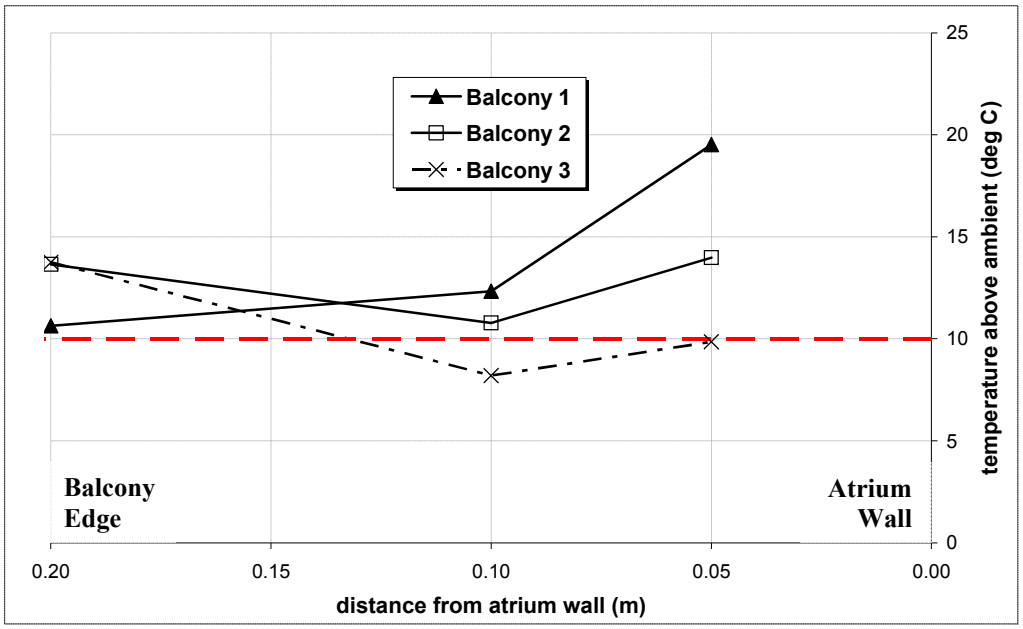
Temperature Profiles	Visual Observations
	

Figure D-27: Experiment 34

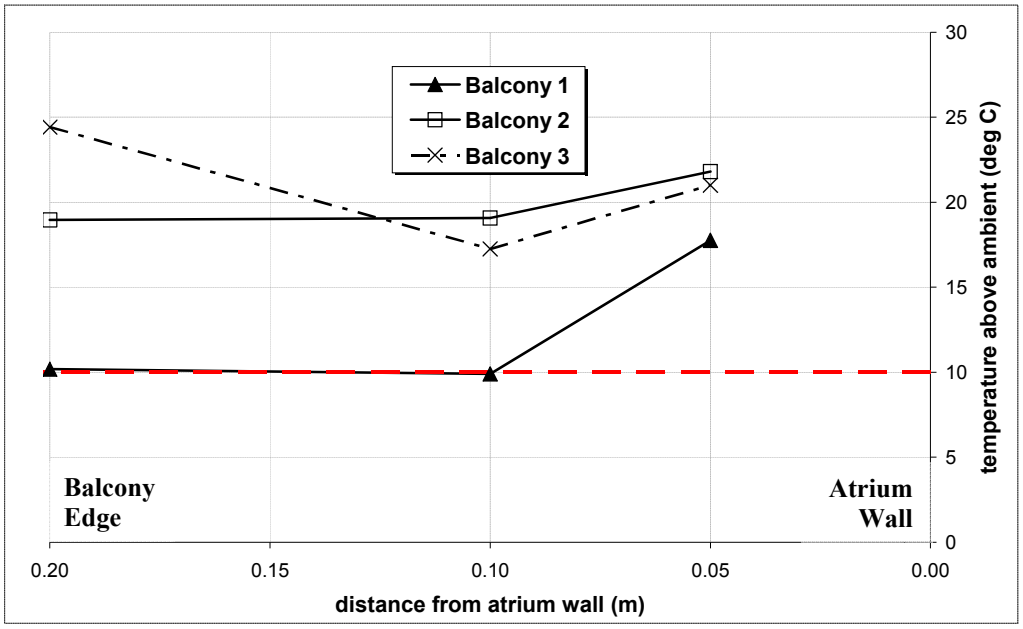


Figure D-28: Experiment 35

TEMPERATURE PROFILES ALONG BALCONY BREADTH

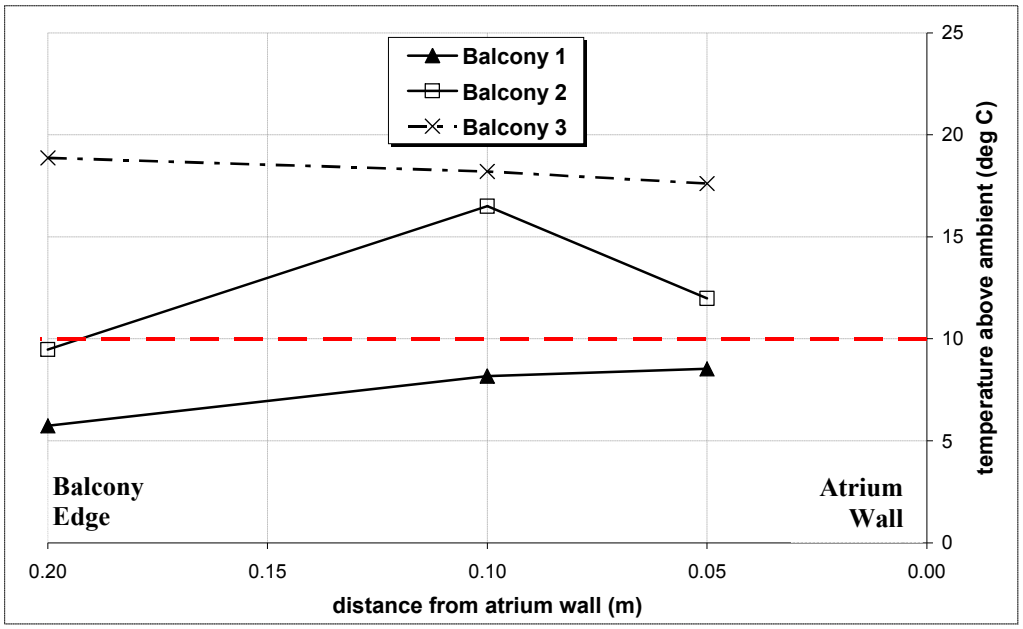
Temperature Profiles	Visual Observations
	

Figure D-29: Experiment 36

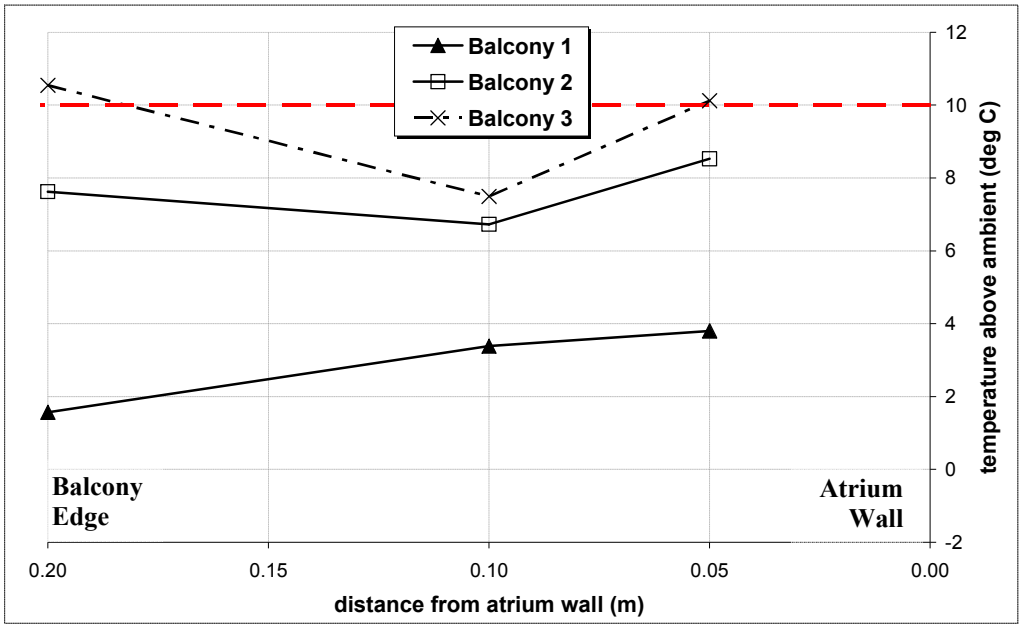


Figure D-30: Experiment 37

TEMPERATURE PROFILES ALONG BALCONY BREADTH

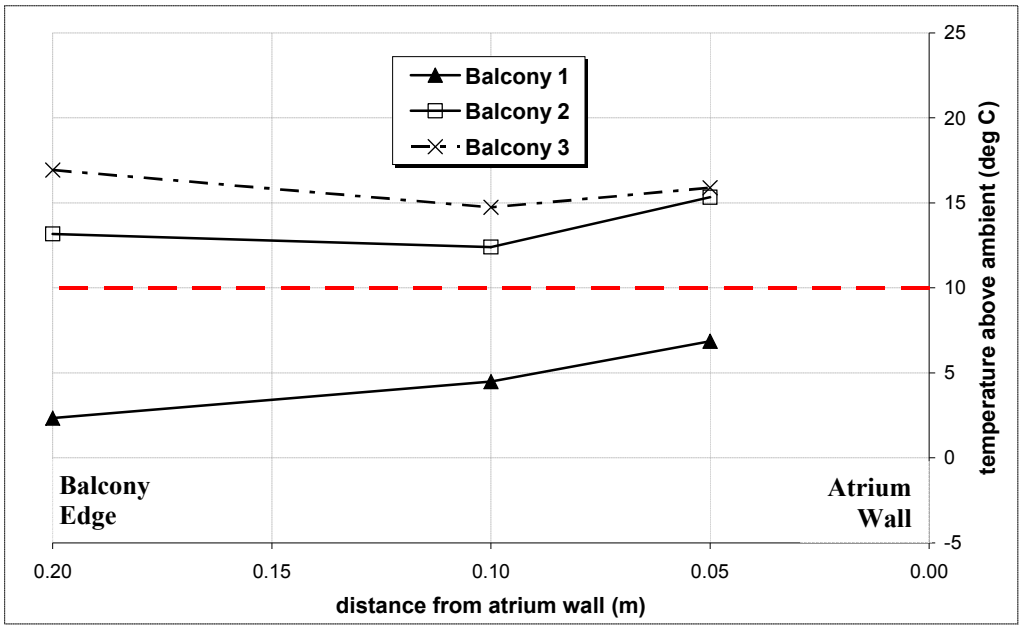
Temperature Profiles	Visual Observations
	

Figure D-31: Experiment 38

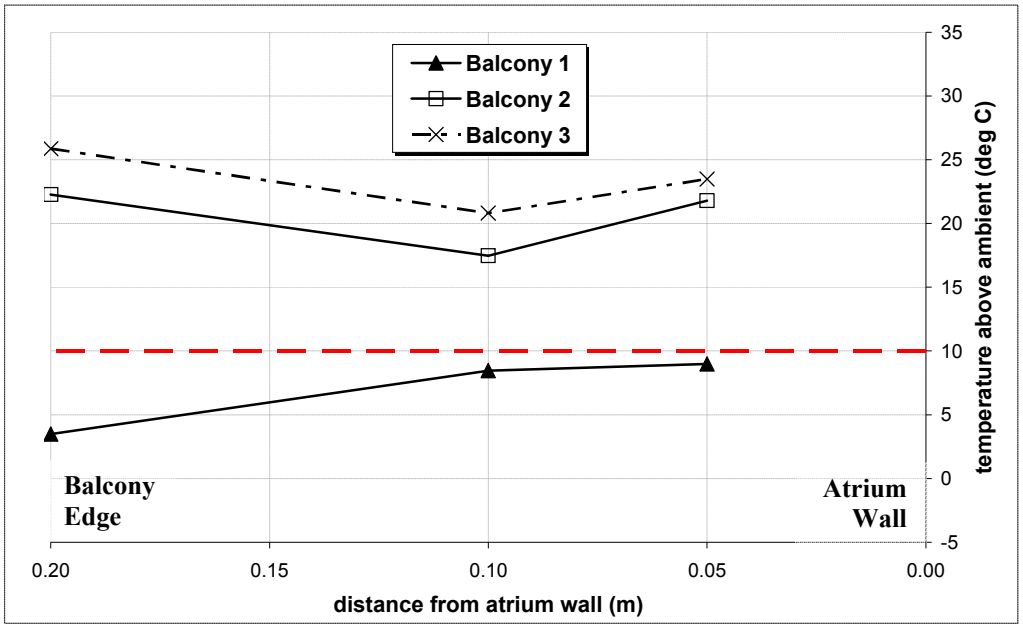
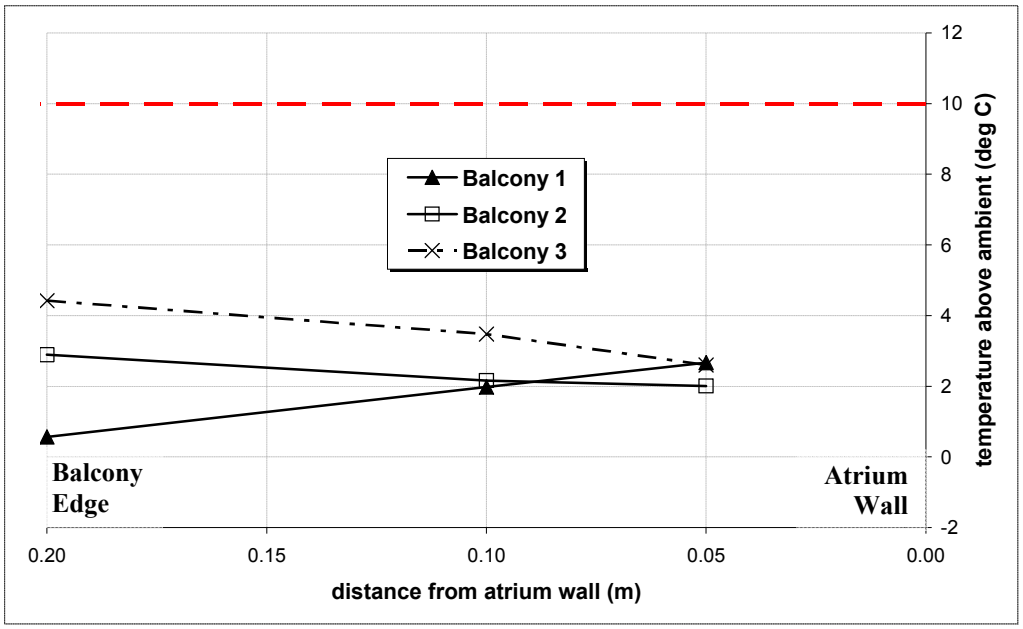
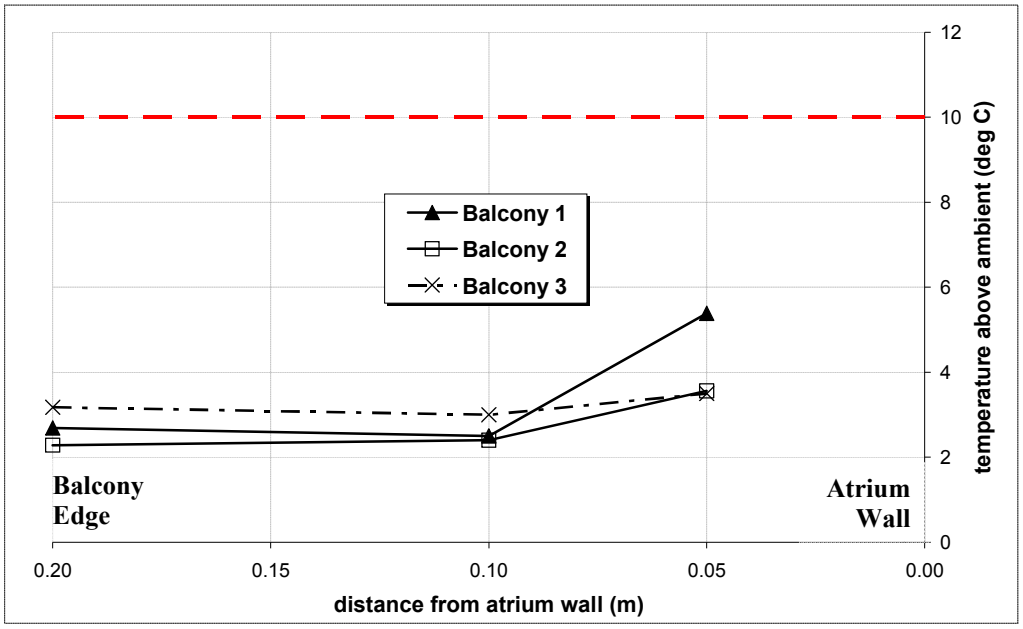
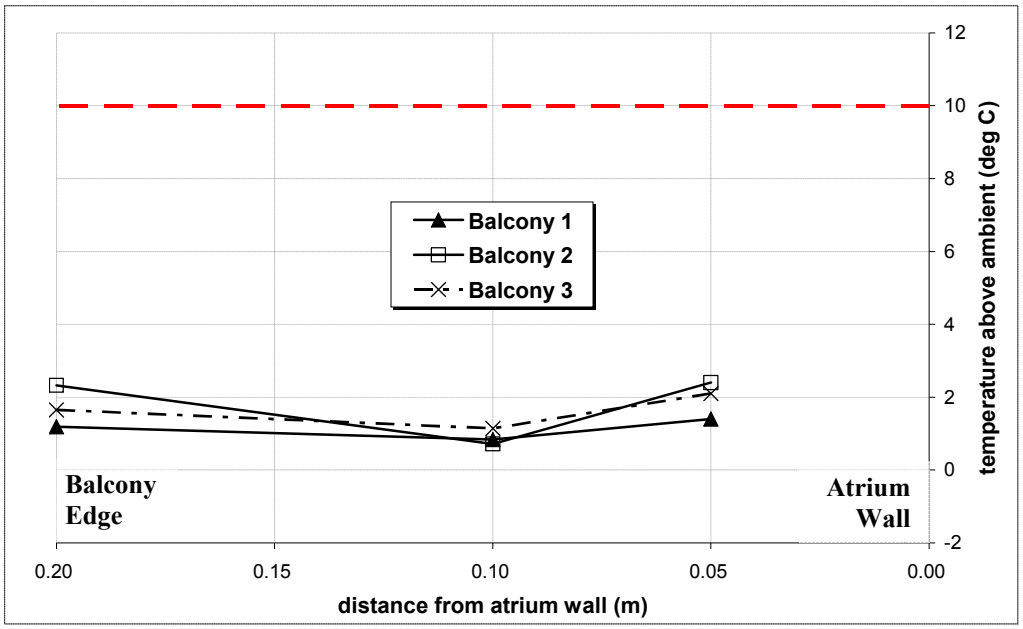
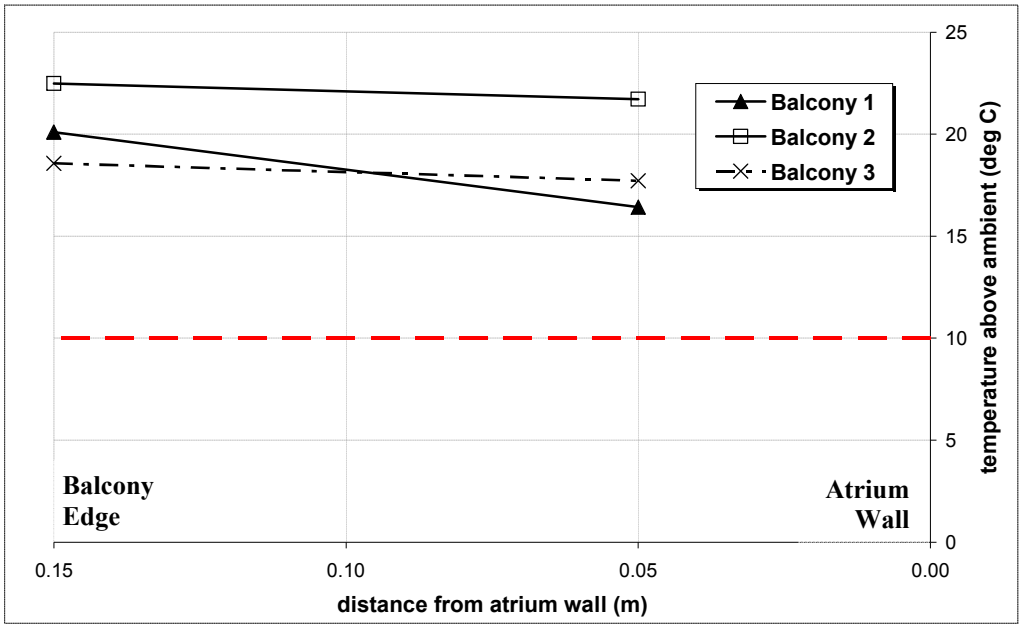


Figure D-32: Experiment 39

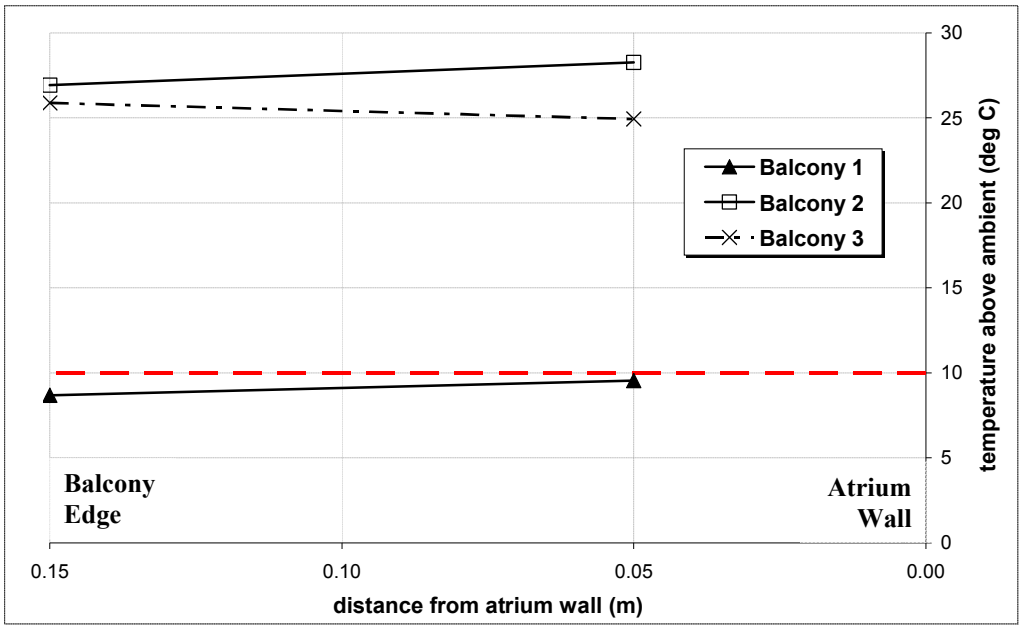
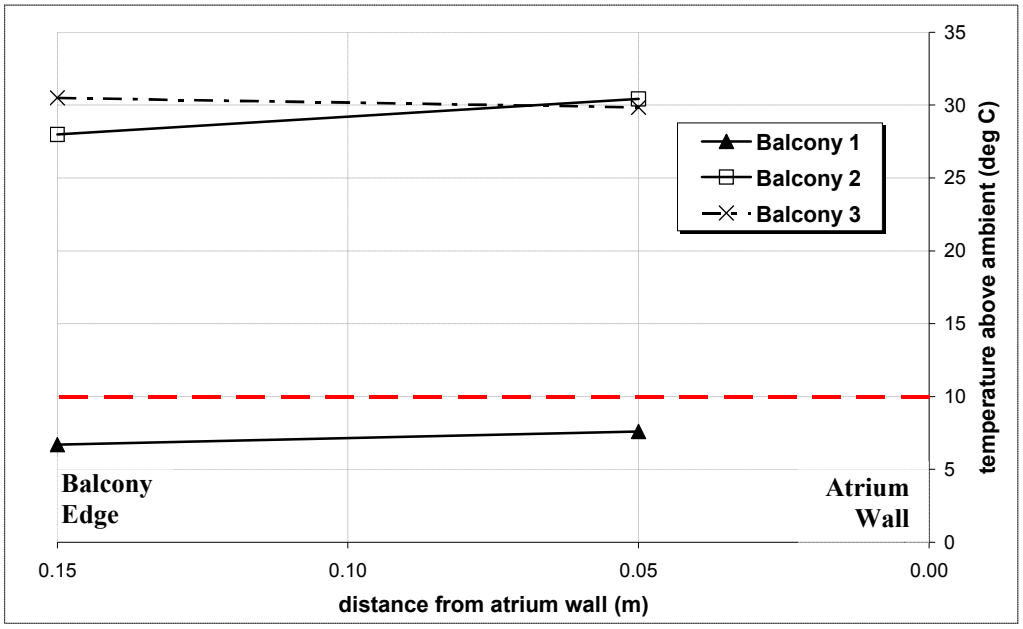
TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-33: Experiment 40	
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-34: Experiment 41	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✗ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-35: Experiment 43	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1
Figure D-36: Experiment 46	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1
Figure D-37: Experiment 47	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1
Figure D-38: Experiment 48	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

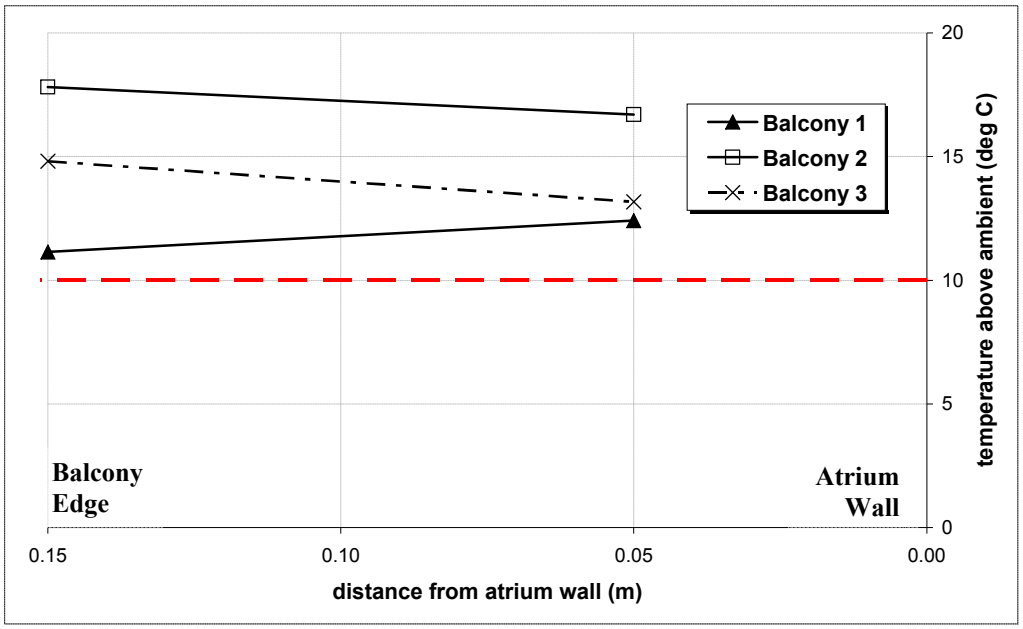
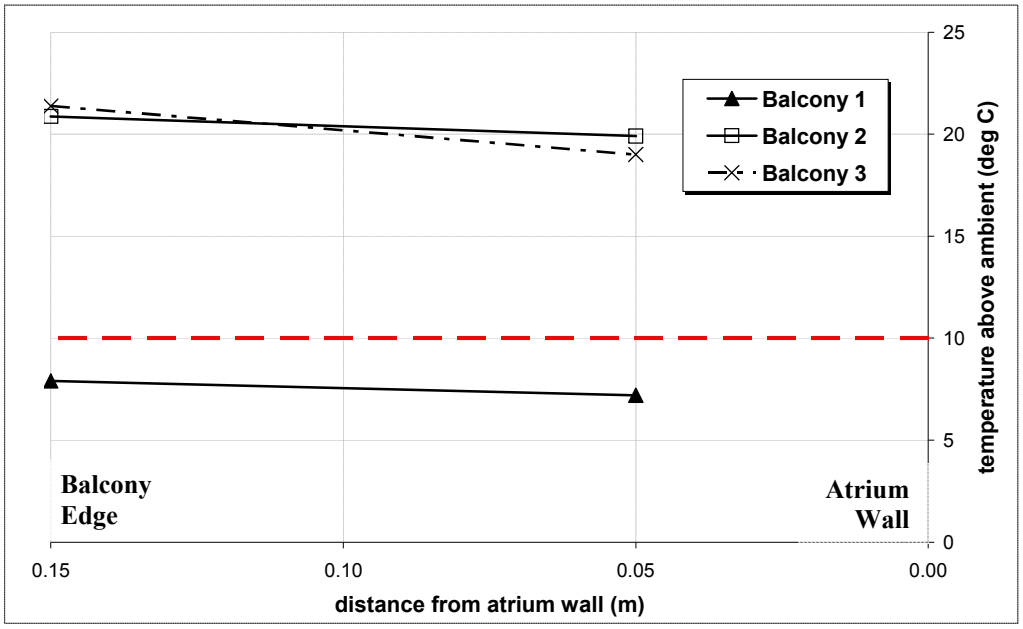
Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓✓ Balcony 1

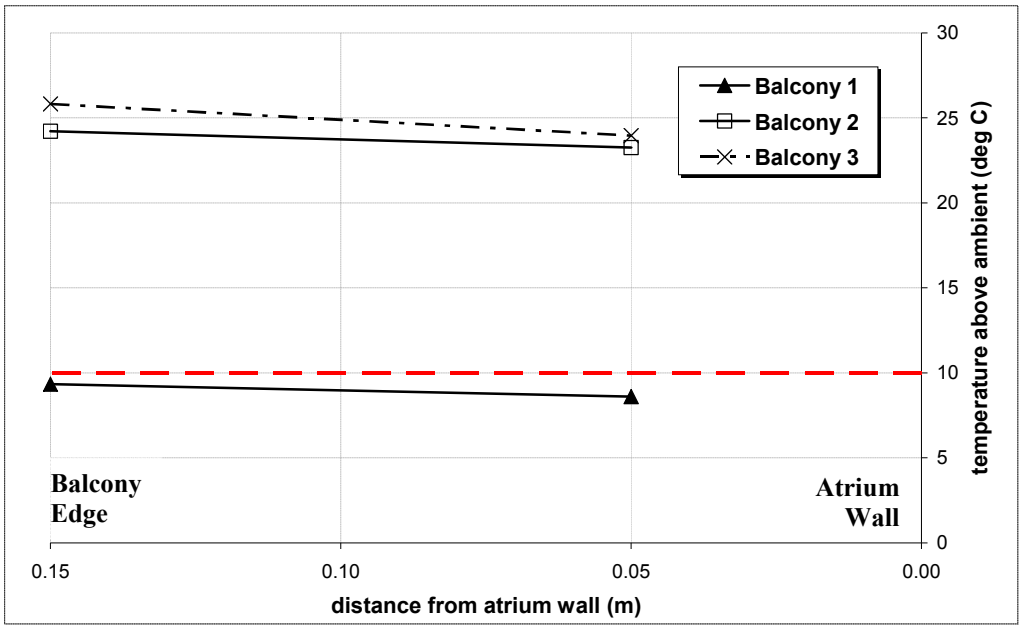
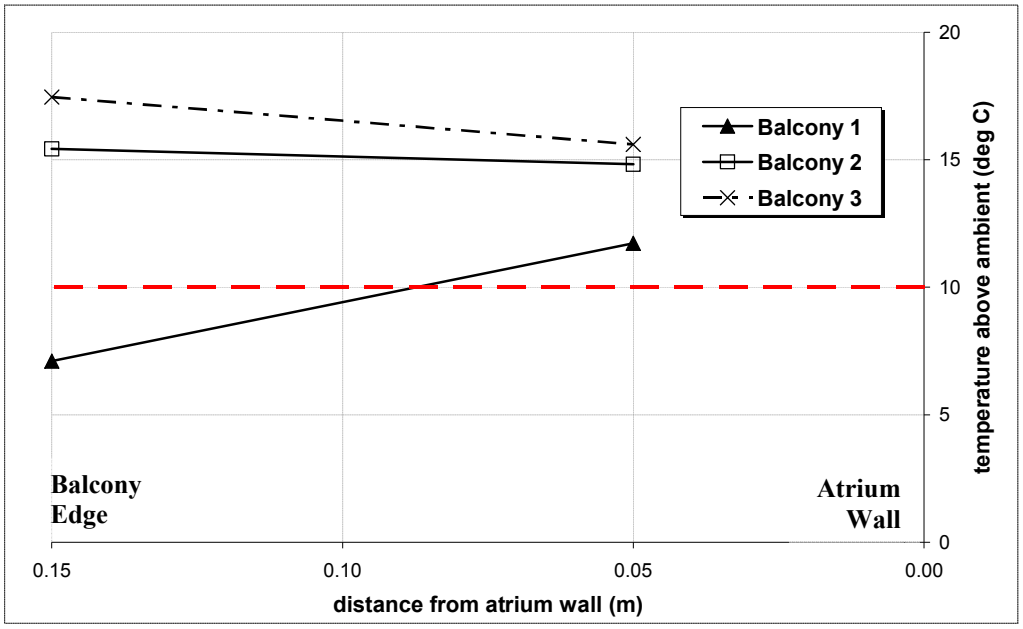
Figure D-39: Experiment 49



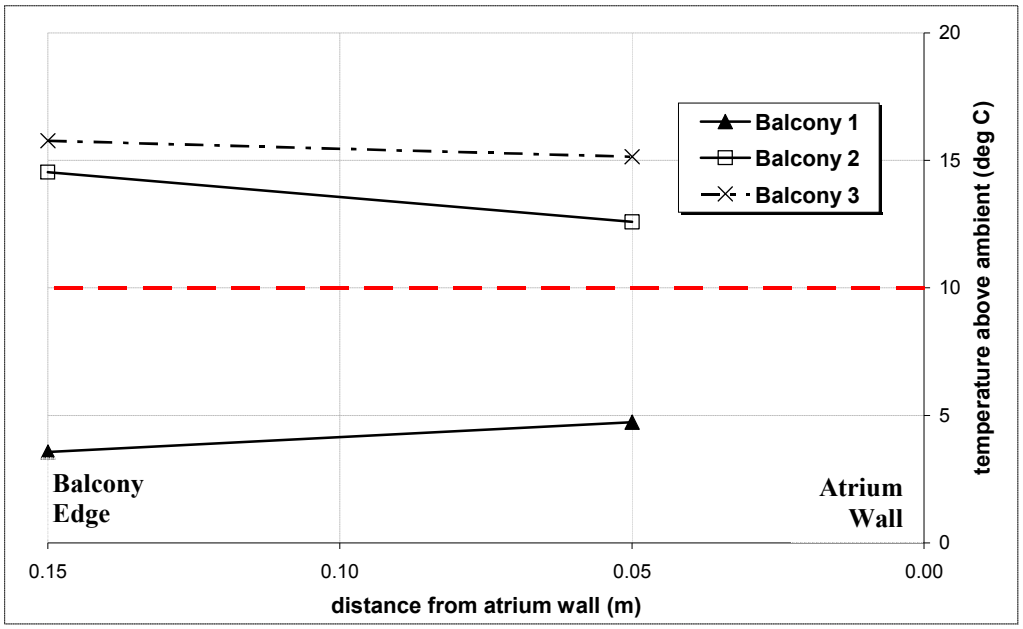
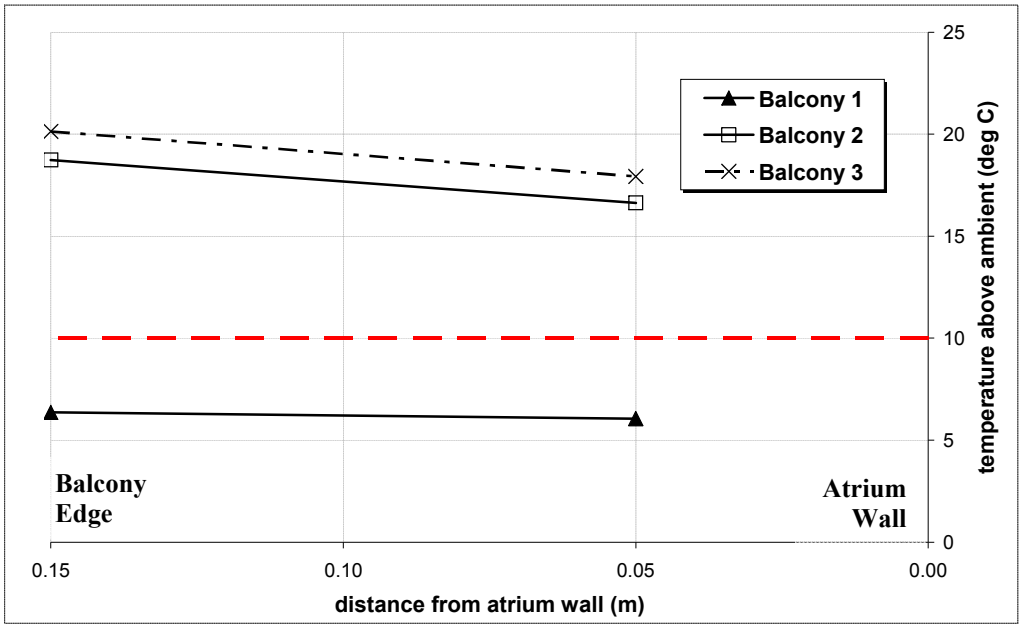
✓✓ Balcony 3
✓✓ Balcony 2
✓✓ Balcony 1

Figure D-40: Experiment 50

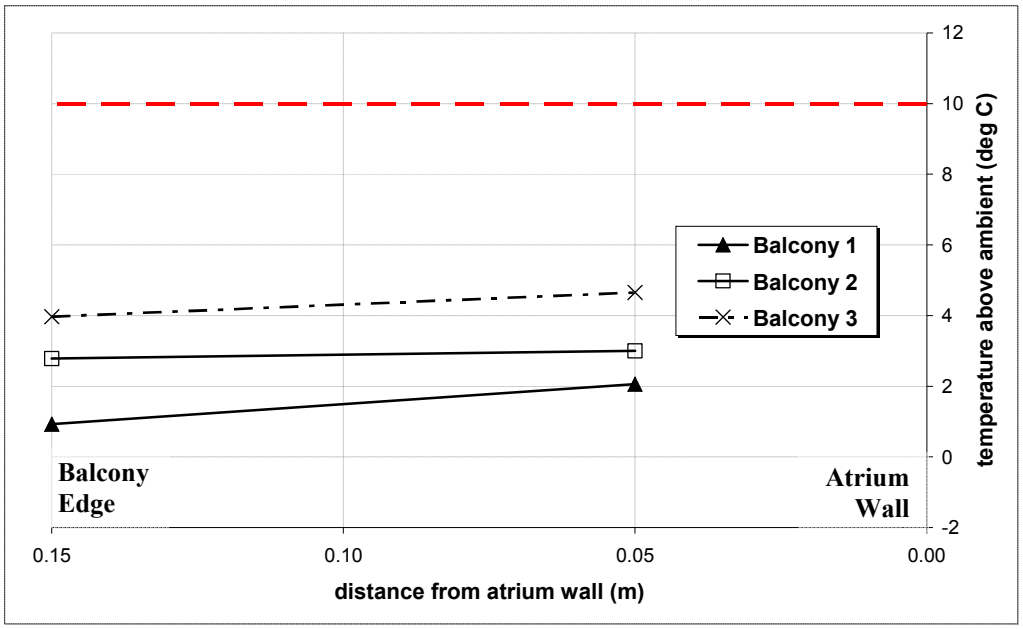
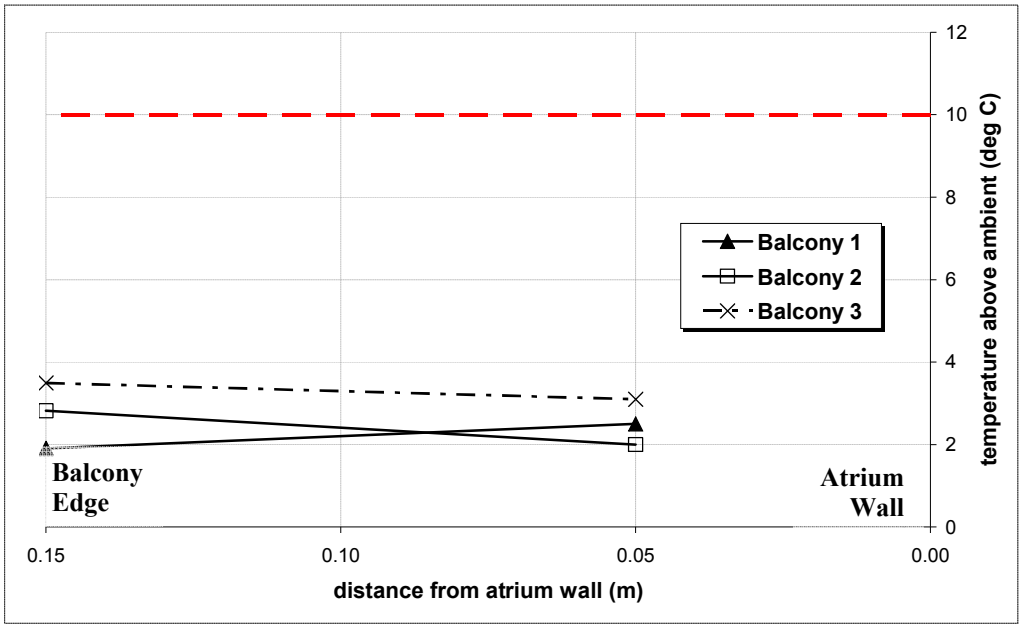
TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure D-41: Experiment 51	
	✓✓ Balcony 3 ✓✓ Balcony 2 ✓ Balcony 1
Figure D-42: Experiment 52	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✓ Balcony 2 ✓ Balcony 1
Figure D-43: Experiment 53	
	✓✓ Balcony 3 ✓ Balcony 2 ✘ Balcony 1
Figure D-44: Experiment 54	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-45: Experiment 55	
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-46: Experiment 56	

TEMPERATURE PROFILES ALONG BALCONY BREADTH

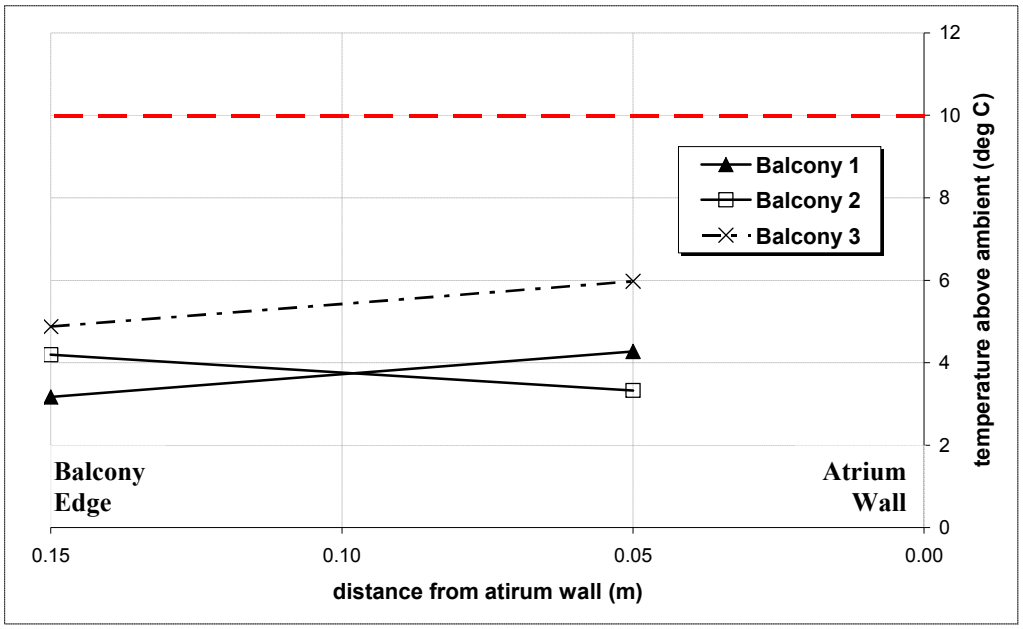
Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1

Figure D-47: Experiment 57

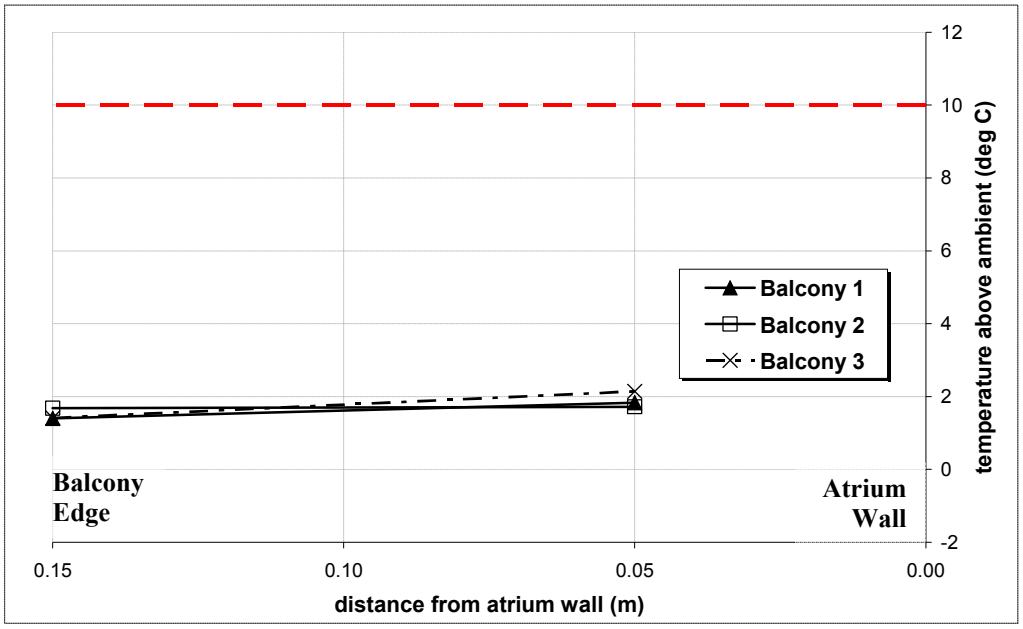
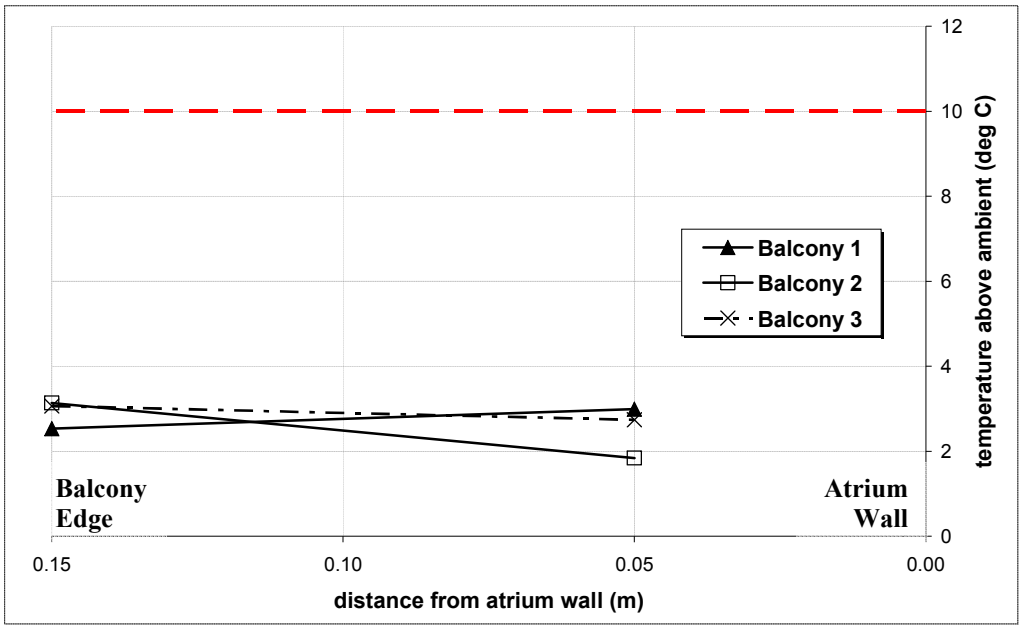
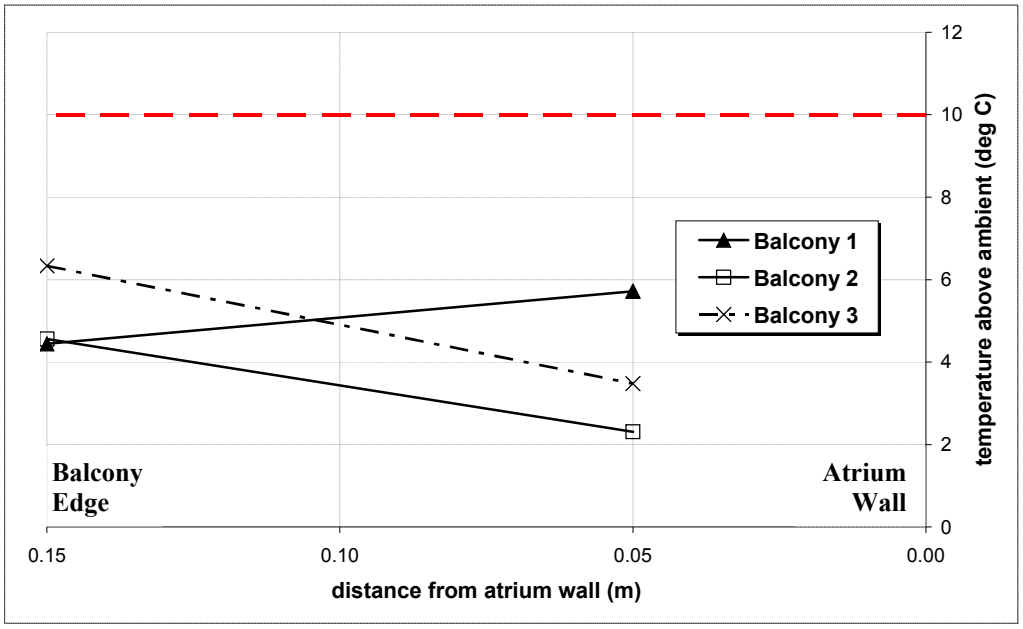


Figure D-48: Experiment 58

TEMPERATURE PROFILES ALONG BALCONY BREADTH

Temperature Profiles	Visual Observations
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-49: Experiment 59	
	✓ Balcony 3 ✗ Balcony 2 ✗ Balcony 1
Figure D-50: Experiment 60	